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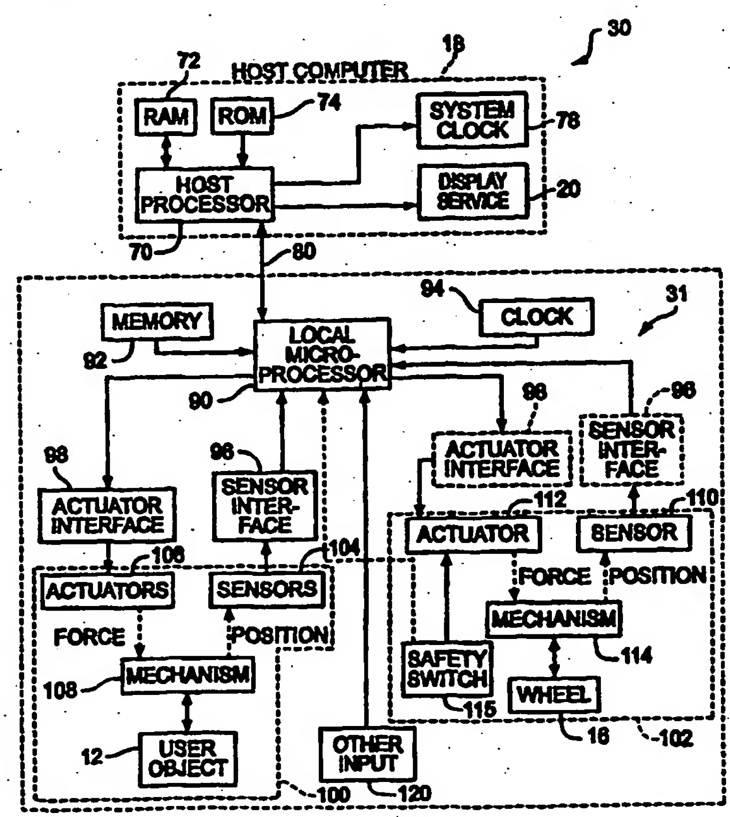
(54) Title: FORCE FEEDBACK CONTROL WHEELS AND KNOBS

(57) Abstract

A force feedback wheel or knob is provided on a mouse or other device to be manipulated by a user. In one embodiment, a rotatable wheel is mounted upon a manipulandum, such as a mouse, and rotates about a wheel axis, where a wheel sensor provides a wheel signal to a host computer indicating a rotary position of the wheel, and a wheel actuator coupled to the rotatable wheel applies a computer–modulated force to the wheel about the wheel axis. The force applied to the wheel can correspond with an event or interaction displayed in a host graphical environment. In other embodiments, a knob on a device allows a user to control functions of the device. The knob is rotatable in a rotary degree of freedom and can be moved in a transverse direction perpendicular to the axis of rotation and/or moved in a linear degree of freedom, allowing the knob to be pushed or pulled by the user. Force feedback is preferably provided using an actuator coupled to the knob. The device controlled by the knob can be, for example, an audio device, a video device, etc. Detent forces can be provided for the knob by overlapping and adjusting ranges of closely-spaced detents in the rotary degree of freedom of the knob.



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FORCE FEEDBACK CONTROL WHEELS AND KNOBS

BACKGROUND OF THE INVENTION

The present invention relates generally to interface devices for allowing humans to interface with electronic and computer devices, and more particularly to mechanical computer interface devices that allow the user to provide input to electronic systems and provide force feedback to the user.

Electronic and computer devices are used in a wide variety of applications. For many devices, a user desires to provide input to a device using a simple, intuitive mechanical control. Control wheels and knobs provide such an intuitive input device for many applications.

In one application, control wheels and knobs are useful to provide input to computer systems. For example, users can interact with a visual environment displayed by a computer on a display device to perform functions on the computer, play a game, experience a simulation or "virtual reality" environment, use a computer aided design (CAD) system, browse the World Wide Web, or otherwise influence events or images depicted on the screen. One visual environment that is particularly common is a graphical user interface (GUI). GUI's present visual images which describe various graphical metaphors of a program or operating system implemented on the computer. Common GUI's include the Windows® operating system from Microsoft Corporation, the MacOS® operating system from Apple Computer, Inc., and the X-Windows GUI for Unix operating systems. The user typically moves a user-controlled graphical object, such as a cursor or pointer, across a computer screen and onto other displayed graphical objects or screen regions, and then inputs a command to execute a given selection or operation. Other programs or environments also may provide user-controlled graphical objects such as a cursor and include browsers and other programs displaying graphical "web pages" or other environments offered on the World Wide Web of the Internet, CAD programs, video games, virtual reality simulations, etc.

A common interface device for providing user input to a GUI is a mouse or trackball. A mouse is moved by a user in a planar workspace to move a graphical object such as a cursor on the 2-dimensional display screen in a direct mapping between the position of the user manipulandum and the position of the cursor. This is typically known as "position control", where the motion of the graphical object directly correlates to motion of the user manipulandum. One drawback to traditional mice is that functions such as scrolling a document in a window and zooming a view displayed on the screen in or out are typically awkward to perform, since the user must use the cursor to drag a displayed scroll bar or click on displayed zoom controls.

These types of functions are often more easily performed by "rate control" devices, i.e. devices that have an indirect or abstract mapping of the user manipulandum to the graphical object, such as pressure-sensitive devices. Scrolling text in a window or zooming to a larger view in a window are better performed as rate control tasks, since the scrolling and zooming are not directly related to the planar position of a mouse. Similarly, the controlled velocity of a simulated vehicle is suitable for a rate control paradigm.

To allow the user easier control of scrolling, zooming, and other like functions when using a mouse, a "scroll wheel" or "mouse wheel" has been developed and has become quite common on computer mice. A mouse wheel is a small finger wheel provided on a convenient place on the mouse, such as between two mouse buttons, which the user may rotate to control a scrolling or zooming function. Most commonly, a portion of the wheel protrudes out of the top surface of the mouse which the user can move his or her finger over. The wheel typically includes a rubber or other frictional surface to allow a user's finger to easily rotate the wheel. In addition, some mice provide a "clicking" wheel that moves between evenly-spaced physical detent positions and provides discrete positions to which the wheel can be moved as well as providing the user with some physical feedback as to how far the wheel has rotated. The wheel is most commonly used to scroll a document in a text window without having to use a scroll bar, or to zoom a window's display in or out without selecting a separate zoom control. The wheel may also be used in other applications, such as a game, drawing program, or simulation.

One problem with existing mouse wheels is that they are quite limited in functionality. The wheel has a single frictional feel to it, and provides the user with very little tactile feedback as to the characteristics of the scrolling or zooming function employed. Even the mouse wheels having physical detents are limited in that the detents are spaced a constant distance apart and have a fixed tactile response, regardless of the scrolling or zooming task being performed or the characteristics of the document or view being manipulated. Providing additional physical information concerning the characteristics of the task that the wheel is performing, as well as allowing the wheel to perform a variety of other tasks in a GUI or other environment, would be quite useful to a user.

In other applications, control wheels and knobs are also quite useful. Often, rotary control knobs offer a degree of control to a user that is not matched in other forms of control devices, such as button or switch controls. For example, many users prefer to use a rotating control knob to adjust the volume of audio output from a stereo or other sound output device, since the knob allows both fine and coarse adjustment of volume with relative ease, especially compared to button controls. Both rotary and linear (slider) knobs are used on a variety of other types of devices, such as kitchen and other home appliances, video editing/playback devices, remote controls, televisions, etc.

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Some control knobs have been provided with "force feedback." Force feedback devices can provide physical sensations to the user manipulating the knob. Typically, a motor is coupled to the knob and is connected to a controller such as a microprocessor. The microprocessor receives sensor signals from the knob and sends appropriate force feedback control signals to the motor so that the motor provides forces on the knob. In this manner, a variety of programmable feel sensations can be output on the knob, such as detents, spring forces, or the like.

One problem occurring in control knobs of the prior art is that the knobs are limited to basic rotary motion. This limits the control options of the user to a simple, one-degree-of-freedom device that does not allow a variety of selection options. In addition, if force feedback is provided on the knob, the limited force feedback and control functionality of the knob limits the user from fully taking advantage of the force feedback to provide more control over desired functions.

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SUMMARY OF THE INVENTION

The present invention is directed to many embodiments involving a force feedback wheel or knob. The wheels and knobs described herein provide greater functionality and relay greater tactile information to the user concerning the control task being performed with the wheel or knob than standard non-force-feedback controls and other limited force feedback controls.

More particularly, an interface device and method for interfacing a user's input with a host computer and providing force feedback to the user includes a user manipulandum contacted and manipulated by a user and moveable in a planar workspace with respect to a ground surface. A manipulandum sensor detects a position of the user manipulandum in the planar workspace and sends a position signal to the host computer indicating a position of the user manipulandum in the workspace. A rotatable wheel is mounted upon the user manipulandum and rotates about a wheel axis, where a wheel sensor provides a wheel signal to the host computer indicating a rotary position of the wheel. A wheel actuator coupled to the rotatable wheel applies a computer-modulated force to the wheel about the wheel axis.

The user manipulandum can include a mouse object or other type of object. In a standard mouse implementation, the manipulandum sensor includes a ball and roller assembly. In a force feedback mouse implementation, one or more additional actuators are included for applying a force to the manipulandum in the workspace. A mechanical linkage having multiple members can be coupled between the manipulandum actuators and the manipulandum. The wheel can be oriented in a variety of ways; for example, the wheel can rotate about an axis parallel to the planar workspace. The wheel actuator can be directly coupled to the wheel, or can be coupled to the wheel by a drive mechanism such as a belt drive. A local microprocessor can also be provided in the interface device to control the actuator to apply the force on the wheel.

The host computer is preferably running a graphical environment, where the force applied to the wheel corresponds with an event or interaction displayed in the graphical environment. The event can be the scrolling of a displayed document as controlled by the sensed rotation of the wheel, or a zooming or panning of a view in the graphical environment. In one embodiment, the cursor's motion is influenced by the rotation of the wheel, such that the event can be an interaction of a cursor with a graphical object. Different modes, such as isotonic and isometric modes, can also be provided, where force sensations appropriate to each mode are applied to the wheel.

In a different embodiment, a force feedback wheel or knob device of the present invention provides input to an electronic device. The knob device includes a wheel rotatably coupled to a housing and rotatable about an axis, a computer-modulated actuator coupled to the wheel for generating a simulated detent sensation on the wheel, where the force detent is

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provided at a predetermined user-preferred rotational position of the wheel, and a sensor that senses rotation of the wheel and provides a wheel signal to the electronic device indicating a rotary position of the wheel. The wheel can be included on a remote control device for remotely sending signals to the electronic device, or on the housing of the electronic device itself. The electronic device can be any of a variety of devices or appliances; for example, a radio can include the force wheel for providing user-preferred detents at radio station frequencies spaced irregularly about the rotational range of the wheel.

In an embodiment of a knob controller device of the present invention, a knob is coupled to a grounded surface. The knob is rotatable in a rotary degree of freedom about an axis extending through the knob, and the knob also moveable in a transverse direction approximately perpendicular to the axis. A rotational sensor detects a position of the knob in the rotary degree of freedom, and a transverse sensor detects a position of the knob in the transverse direction. An actuator is coupled to the knob to output a force in the rotary degree of freedom about the axis, thus providing force feedback. In a preferred embodiment, the knob is moveable in multiple transverse directions. For example, the transverse sensor includes a switch that detects when the knob is moved in a transverse direction; the switch can be a hat switch having multiple individual switches, for example. In one embodiment, the knob is moveable in four transverse directions spaced approximately orthogonal to each other.

Furthermore, a local microprocessor can be included to control the force feedback on the knob. The microprocessor receives sensor signals from the rotary and transverse sensors and controls a function of a device in response to the sensor signals. The device can also include a display, wherein an image on said display is changed in response to manipulation of the knob in the transverse direction. A method of the present invention for controlling functions of a device from input provided by a knob similarly uses sensor signals from a rotary sensor and a transverse sensor to control at least one function of a device, such as adjusting a frequency of a radio tuner or updating a displayed image based on at least one of the sensor signals.

In another aspect of the present invention, a knob is coupled to a grounded surface, where the knob is rotatable in a rotary degree of freedom about an axis extending through the knob. The knob is also moveable in a linear degree of freedom approximately parallel to the axis. A rotational sensor and a linear sensor detect positions of the knob in the respective degrees of freedom. An actuator is also coupled to the knob and operative to output a force in the rotary degree of freedom about the axis, thereby providing force feedback to the knob. The linear degree of freedom of the knob allows it to be pushed and/or pulled by the user, where the push or pull motion is detected by the linear sensor. A transverse degree of freedom and a local microprocessor can also be included.

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In a different aspect of the present invention, a method for providing detent forces for a force feedback control includes outputting a first force by an actuator on a user manipulatable object, such as a rotary knob, for a first detent when the user object is moved within a range of the first detent. The first force assists movement of the user object toward an origin position of the first detent and resists movement away from the origin position. A second force for a second detent is also output on the user object when the user object is moved within a range of the second detent, similar to the first force. A portion of the range of the first detent overlaps a portion of the range of the second detent. The overlapped portions of the ranges preferably modify the second force such that a force at the beginning point of the second detent range has less magnitude than a force at an endpoint of the second detent range. Preferably, the first force and second force each have a magnitude that increases the further that the user object is positioned from that detent's origin. The direction of the knob can change the range endpoint magnitudes such that if the knob is moved in the opposite direction, the first-encountered point of the first detent range has a lesser magnitude than the last-encountered point.

In another aspect of the present invention, a method for providing detent forces for a force feedback control includes defining a periodic wave and using at least a portion of the periodic wave to define a detent force curve. The detent force curve defines a force to be output on a user manipulatable object, such as a rotary knob, based on a position of the user manipulatable object in a degree of freedom. The detent force curve is then used to command the force on the user manipulatable object as output by an actuator. The type, period and magnitude can be specified for the periodic wave. The detent force curve can be defined by specifying a portion of said periodic wave to be the width of the detent force curve, specifying a phase and an offset to be applied to said periodic wave to define the detent force curve, and/or specifying an increment distance between successive detents.

The apparatus and method of the present invention provides an interface device including a force feedback wheel or knob that allows a user to conveniently provide input to manipulate functions or events in a host computer application program or electronic device. The wheel allows substantially greater control and flexibility than previous wheels, and the force feedback allows the wheel to control a variety of useful functions in a graphical environment which prior wheels are not able to control. The linear and transverse degrees of freedom of the knob embodiment allow the user to select functions, settings, modes, or options with much greater ease and without having to take his or her hand off the knob. Force feedback detent implementations of the present invention provide overlapping detent ranges to allow more accurate control of a knob by a user within closely-spaced detents, and an efficient, convenient method for defining detents from periodic waves.

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These and other advantages of the present invention will become apparent to those skilled in the art upon a reading of the following specification of the invention and a study of the several figures of the drawing.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective view of one embodiment of a mouse interface system including a force feedback wheel of the present invention;

Figure 2 is a perspective view of a second embodiment of a force feedback mouse interface system including the force feedback wheel of the present invention;

Figures 3a and 3b are perspective views of alternate embodiments of an interface device including the force feedback wheel of the present invention;

Figure 4 is a block diagram of the interface system including a force feedback wheel of the present invention;

Figures 5 and 6 are perspective views of two embodiments of a direct drive mechanical portion of the interface device for the force feedback wheel;

Figure 7 is a perspective view of an embodiment of a belt drive mechanical portion of the interface device for the force feedback wheel;

Figure 8 is a perspective view of an embodiment of a belt drive mechanism allowing the wheel to be depressed like a button; and

Figure 9 is a diagrammatic illustration of a GUI and graphical objects which can be manipulated using the force feedback wheel of the present invention.

Figure 10 is a perspective view of one embodiment of a device including a control knob of the present invention;

Figure 11 is a diagrammatic view of a display allowing the user to use the knob of the present invention to select features of the device;

Figure 12a is a perspective view of one embodiment of the mechanism for implementing the control knob of the present invention;

Figure 12b is a side elevational view of the embodiment of Fig. 12a;

Figure 13a is a perspective view of a second embodiment of the mechanism for implementing the control knob of the present invention;

Figure 13b is a top plan view of a unitary plate used in the embodiment of Fig. 13a;

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Figure 13c is a side elevational view of the embodiment of Fig. 13a;

Figure 14 is a perspective view of a linear slider control of the present invention;

Figures 15a-15d illustrate nonoverlapping, overlapping, and hysteresis features of force detent profiles;

Figures 16a-16e are graphs illustrating the creation of detent force profiles from periodic waves according to the present invention; and

Figure 17 is a block diagram of a control system for the control knob of the present invention.

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DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIGURE 1 is a perspective view of a first embodiment of the present invention. A mouse 12 includes a force feedback mouse wheel 16 of the present invention. Mouse 12 rests on a ground surface 44 such as a tabletop or mousepad. A user grasps the mouse 12 and moves the mouse in a planar workspace on the surface 44 as indicated by arrows 22. Mouse 12 may be moved anywhere on the ground surface 44, picked up and placed in a different location, etc. A frictional ball and roller assembly (not shown) is provided on the underside of the mouse 12 to translate the motion of the mouse 12 into electrical position signals, which are sent to a host computer 18 over a bus 17 as is well know to those skilled in the art. In other embodiments, different mechanisms can be used to convert mouse motion to position or motion signals received by the host computer. It should be noted that the term "mouse" as used herein indicates an object 12 generally shaped to be grasped or contacted by a user from above and moved within a substantially planar workspace (and additional degrees of freedom if available). Typically, a mouse is a smoothly- or angular-shaped compact unit that snugly fits under a user's hand, fingers, and/or palm, but can be implemented as other objects as well.

Mouse 12 includes buttons 15 and a mouse wheel 16. Buttons 15 can be pressed by the user to provide an associated signal to the host computer 18 over bus 17. Additional buttons can be provided in other embodiments of mouse 12. Mouse wheel 16 of the present invention is provided, for example, between buttons 15 to allow easy access for a user's finger. A wheel 16 can alternatively or additionally be provided in a location easily accessed by the user's thumb. The wheel as shown only partially protrudes from an aperture 13 in the housing of the mouse 12 and preferably is provided with a frictional surface, such as a rubber-like surface or a series of ridges or bumps to allow the user's finger to grip the wheel more easily. Wheel 16 is operative to rotate in place in when the user's finger pushes the wheel in either rotational direction. When the user rotates the wheel, a corresponding signal indicating the amount of rotation and the direction of rotation is sent to host computer 18 over bus 17. For example, the wheel signal can be used by host computer to scroll a document in a window, pan a view, or zoom a view. The wheel 16 is coupled to an actuator in mouse 12 which applies forces to wheel 16, which is described in greater detail below. Typically, wheel 16 is provided in a Y-orientation and rotates about an axis oriented in the X-direction as shown in Figure 1, where the wheel controls vertical (Y-direction) motion of a graphical object displayed by host 18. In other embodiments, a wheel can be provided in an X-orientation that rotates about a Y-axis, and which can control horizontal (X-direction) motion of a host graphical object. In yet other embodiments, two or more wheels 16 can be provided on mouse 12 in different orientations to provide the user with multiple wheel controls. In still other embodiments, wheel 16 can be provided as a trackball (or similar

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approximately spherical object) provided in a socket in mouse 12, and which can be moved in both X- and Y- directions and have forces applied thereto.

Furthermore, in some embodiments, wheel 16 may be depressed by the user as indicated by arrow 19. The wheel, when pressed, causes contacts to be electrically connected and provides a signal to host computer 18. Wheel 16 thus can also operate as an additional mouse button 15. A mechanical/electrical interface (not shown) is preferably included to sense manipulations of the wheel 16 and transmit force to the wheel. In the preferred embodiment, power is provided to actuators over bus 17 (e.g. when bus 17 includes a USB interface). The structure and operation of wheel 16 and the interface is described in greater detail with respect to Figures 5-9.

Host computer 18 is preferably a personal computer or workstation, such as an IBM-PC compatible computer or Macintosh personal computer, or a SUN or Silicon Graphics workstation. For example, the computer 18 can operate under the Windows™ or MS-DOS operating system in conformance with an IBM PC AT standard. Alternatively, host computer system 18 can be one of a variety of home video game systems commonly connected to a television set, such as systems available from Nintendo, Sega, or Sony. In other embodiments, host computer system 18 can be a "set top box" which can be used, for example, to provide interactive television functions to users, or a "network-" or "internet-computer" which allows users to interact with a local or global network using standard connections and protocols such as used for the Internet and World Wide Web. Host computer preferably includes a host microprocessor, random access memory (RAM), read only memory (ROM), input/output (I/O) circuitry, and other components of computers well-known to those skilled in the art.

Host computer 18 preferably implements a host application program with which a user is interacting via mouse 12 and other peripherals, if appropriate. The application program includes force feedback functionality to provide appropriate force signals to mouse 12. For example, the host application program can be a GUI, simulation, video game, Web page or browser that implements HTML or VRML instructions, scientific analysis program, virtual reality training program or application, or other application program that utilizes input of mouse 12 and outputs force feedback commands to the mouse 12. Herein, for simplicity, operating systems such as Windows™, MS-DOS, MacOS, Unix, etc. are also referred to as "application programs." In one preferred embodiment, an application program utilizes a graphical user interface (GUI) to present options to a user and receive input from the user. Herein, computer 18 may be referred as displaying "graphical objects" or "computer objects." These objects are not physical objects, but are logical software unit collections of data and/or procedures that may be displayed as images by computer 18 on display screen 20, as is well known to those skilled in the art. A displayed cursor, a view displayed by a GUI window, a portion of a document displayed in the window, or a simulated cockpit of an aircraft can all be considered graphical objects. The host application program checks for input signals received from the mouse 12, displays updated

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graphical objects and other events as appropriate, and outputs force signals across bus 17 to mouse 12 to control forces output on wheel 16, as described in greater detail below. In alternate embodiments, a separate local microprocessor can be included in mouse 12 to locally control force output on wheel 16. Such a microprocessor can be provided in embodiments, such as the embodiment of Figure 1, having no other force feedback except through wheel 16. A local microprocessor is described in greater detail with respect to Figure 4.

Display device 20 is typically included in host computer 18 and can be a standard display screen (LCD, CRT, etc.), 3-D goggles, or any other visual output device. Typically, the host application provides images to be displayed on display device 20 and/or other feedback, such as auditory signals. For example, display screen 20 can display images from a GUI. Images describing a first person point of view can be displayed, as in a virtual reality game or simulation. Or, images describing a third-person perspective of objects, backgrounds, etc. can be displayed.

Mouse 12 can be used, for example, to control a computer-generated graphical object such as a cursor or pointer displayed in a graphical computer environment, such as a GUI. The user can move the mouse in 2D planar workspace to move the cursor to graphical objects in the GUI or perform other tasks. The user may use wheel 16 to scroll text documents, perform zooming functions on views in windows, perform panning functions, or perform other rate control tasks. Forces output on wheel 16 provide information about the rate control task performed by the wheel, and allow the user to perform additional control functions as described with reference to Figure 9. For example, the computer system may provide force feedback commands to the wheel when the user moves the graphical object against a generated surface such as an edge of a window, a virtual wall, etc. It thus appears and feels to the user that the graphical object is contacting a real surface. In some embodiments, the user may influence the movement of the cursor with the rotation of wheel 16. In other graphical environments, such as a virtual reality video game, a user can be controlling a computer player or vehicle in the virtual environment by manipulating the mouse 12 and wheel 16.

There are two primary "control paradigms" of operation for mouse 12: position control and rate control. Position control is the more typical control paradigm for mouse and similar controllers, and refers to a mapping of mouse 32 in which displacement of the mouse in physical space directly dictates displacement of a graphical object. Under a position control mapping, the computer object does not move unless the user manipulandum is in motion. Also, "ballistics" or other non-linear adjustments to cursor position can be used, in which, for example, small motions of the mouse have a different scaling factor for cursor movement than large motions of the mouse, to allow more control of small cursor movement. As shown in Figure 1, the host computer may have its own "host frame" 28 which is displayed on the display screen 20. In contrast, the mouse 12 has its own "local frame" 30 in which the mouse 12 is moved. In a

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position control paradigm, the position (or change in position) of a user-controlled graphical object, such as a cursor, in host frame 30 corresponds to a position (or change in position) of the mouse 12 in the local frame 28.

Rate control is also used as a control paradigm. This refers to a mapping in which the displacement of a user manipulandum along one or more provided degrees of freedom is abstractly mapped to motion or rate of a computer-simulated object under control. There is not a direct physical mapping between physical object (mouse) motion and computer object motion.

The mouse 12 is useful for both position control ("isotonic") tasks and rate control ("isometric") tasks. For example, as a traditional mouse, the position of mouse 12 in its local frame 30 workspace can be directly mapped to a position of a cursor in host frame 28 on display screen 20 in a position control paradigm. Also, the mouse wheel 16 can be rotated in its degree of freedom against an opposing output force to command rate control tasks in an isometric mode. Wheel 16 can also be used for position control tasks, as described in greater detail below.

FIGURE 2 is a perspective view of a second embodiment 30 of a mouse device using the force feedback mouse wheel 16 of the present invention. Force feedback mouse interface system 30 is capable of providing input to a host computer based on the user's manipulation of the mouse and capable of providing force feedback to the system based on events occurring in a program implemented by the host computer. Mouse device 30 includes added force feedback functionality over the embodiment 12 of Figure 1 in that the planar degrees of freedom of mouse 32 are provided with force feedback in addition to the wheel 16 being provided with force feedback. Mouse system 30 includes an interface device 31 including a mouse 32 and an interface 34; and a host computer 18.

Mouse 32, similar to mouse 12 of Figure 1, is an object that is preferably grasped or gripped and manipulated by a user. In the described embodiment, mouse 32 is shaped so that a user's fingers or hand may comfortably grasp the object and move it in the provided degrees of freedom in physical space. One or more buttons 15 allow the user to provide additional commands to the computer system. A thumb button (not shown) can also be provided on mouse 32. One or more of the buttons 15 may command specific force feedback features of the system 30, as described below. Mouse 32 is preferably supported upon a grounded pad 42, which is supported by grounded surface 44.

It will be appreciated that a great number of other types of user manipulandums ("user manipulatable objects" or "physical objects") can be used with the method and apparatus of the present invention in place of or in addition to mouse 32. For example, such objects may include a sphere, a puck, a joystick, cubical- or other-shaped hand grips, a receptacle for receiving a finger or a stylus, a flat planar surface like a plastic card having a rubberized, contoured, and/or

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bumpy surface, or other objects. Other examples of a user object 32 are described below with reference to Figures 3a and 3b.

Mouse 32 (or other manipulandum) is also provided with a mouse wheel 16 as described with reference to Figure 1. Mouse wheel 16 is provided with force feedback separately from the mouse 32, e.g. an actuator separate from actuators that drive mouse 32 can be used to provide forces on wheel 16. The functions controlled by wheel 16 can be independent of the functions controlled by the planar movement of mouse 32 in its workspace. Alternatively, the functions controlled by wheel 16 can be synchronized or added to functions controlled by planar mouse movement, as described in greater detail below. Wheels 16 in different orientations, or multiple wheels or a trackball, can be provided on mouse 32 as described with reference to mouse 12.

Interface 34 is provided in a housing 33 of the mouse interface device 31 and interfaces mechanical and electrical input and output between the mouse 32 and host computer 18. Interface 34 provides multiple degrees of freedom to mouse 32; in the preferred embodiment, two linear, planar degrees of freedom are provided to the mouse, as shown by arrows 22. In other embodiments, greater or fewer degrees of freedom can be provided, as well as rotary degrees of freedom. A mechanical linkage (not shown) preferably couples the mouse 32 to sensors and actuators of the device 31; some examples of such a linkage are described in copending PCT application WO 98/24183, incorporated by reference herein.

In a preferred embodiment, the user manipulates mouse 32 in a planar workspace, and the position of mouse 32 is translated into a form suitable for interpretation by position sensors of the interface 34. The sensors track the movement of the mouse 32 in planar space and provide suitable electronic signals to an electronic portion of interface 34. The interface 34 provides position information to host computer 18. An electronic portion of interface 34 may be included within the housing 33 to provide electronic signals to host computer 18, as described below with reference to Figure 4. In addition, host computer 18 and/or interface 34 provide force feedback signals to actuators coupled to interface 34, and actuators generate forces on members of the mechanical portion of the interface 34 to provide forces on mouse 32 in provided or desired degrees of freedom and on wheel 16 in its rotary degree of freedom. The user experiences the forces generated on the mouse 32 as realistic simulations of force sensations such as jolts, springs, textures, "barrier" forces, and the like.

The interface 34 can be coupled to the computer 18 by a bus 37, which communicates signals between interface 34 and computer 18 and also, in the preferred embodiment, provides power to the interface 34 (e.g. when bus 17 includes a USB interface). In other embodiments, signals can be sent between interface 34 and computer 18 by wireless transmission/reception. The interface 34 can also receive inputs from other input devices or controls that are associated with mouse system 30 and can relay those inputs to computer 18, such as buttons 15.

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Host computer 18 is described above with reference to Figure 1. The host application program checks for input signals received from the mouse 32, and outputs force values and/or commands to be converted into forces on mouse 32 and on wheel 16. Suitable software drivers which interface force feedback application software with computer input/output (I/O) devices are available from Immersion Human Interface Corporation of San Jose, California.

Mouse system 30 can be used for both position control and rate control. Under a position control mapping, the positions of mouse 32 and a graphical object such as a cursor are directly mapped, as in normal mouse operation. "Ballistics", as described above, can also be provided, and these adjustments can be used in mouse system 30 if desired. Mouse system 30 can also provide a rate control mode in which the displacement of mouse 32 in a particular direction against an opposing output force can command rate control tasks in an isometric mode, as described in U.S. Patent no. 5,825,308, incorporated by reference herein. Furthermore, mouse wheel 16 can also control position and/or rate control tasks independently of the position of the mouse 32 in its workspace, as described in greater detail below.

The mouse system 10 can also include an indexing function or "indexing mode" which allows the user to redefine the offset between the positions of the mouse 32 in the local frame 30 and a user-controlled graphical object, such as a cursor, in the host frame 28. A hand weight safety switch can also be provided as described in greater detail in patent 5,825,308. Other features of the present invention are also provided using force feedback functionality. For example, a thumb button (not shown) or other button 15 can toggle a force functionality mode in which designated graphical objects or regions displayed on screen 20 have other functions enabled by force feedback to wheel 16. This is described in greater detail with respect to Figure 9.

FIGURES 3a and 3b illustrate other embodiments of an interface device and user manipulandum which can incorporate the features of the present invention. In Figure 3a, a hand-held remote control device 50 can be used to access the functions of an electronic device or appliance remotely by a user. For example, remote control 50 can be used to select functions of a television, video cassette recorder, sound stereo system, home computer, kitchen appliance, etc. Such control devices typically provide wireless operation by transmitting input signals using an electromagnetic beam that is detected by a detector on the electronic device. Or, remote control 50 can select functions of an internet or network computer connected to a television. For example, one popular device is Web-TV™, which is connected to a television and displays internet information such as web pages on the television screen. Remote control 50 may include buttons 52 for selecting options of the device or appliance, of the application program running on the device, of web pages, etc. Herein, the term "electronic device" is intended to include all such devices as well as a host computer 18 as described above.

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Remote control 50 also includes a control knob 54 (which is also considered a "wheel" as referenced herein). Knob 54 can be oriented with an axis of rotation approximately perpendicular to the surface of the device 50, as shown in Fig. 3a. Alternatively, the knob 54 can be oriented similarly to the mouse wheel 16, with the axis of rotation approximately parallel to the device surface. Knob 54 is provided with force feedback similarly to the mouse wheel 16 described with reference to Figures 1 and 2 to control a variety of functions of the controlled device or appliance, where the force feedback is integrally implemented with the control functions. For example, force detents can be provided by an actuator on knob 54, which are forces that attract the knob to a particular rotational position and resist movement of the knob away from that position. The position can correspond to a particular network or station broadcast on the television, thus making channel selection easier for the user. Alternatively, a force detent does not provide attraction or repulsive forces, but instead provides a force "bump" to indicate a particular position on the knob has been rotated past. Additional knobs with such detents can be provided for additional functions, such as volume control for sound speakers, fast forward or rewind of a video cassette recorder or computer-displayed movie (such as a DVD movie), scrolling a displayed document or web page, etc. Alternatively, a single knob 54 can be used for a variety of different functions, where the function of the knob (volume, channel selection, etc.) can be selected with a separate button or switch.

Another type of force sensation that can be output on knob 54 is a spring force. The spring force can provide resistance to rotational movement of the knob in either direction to simulate a physical spring on the knob. This can be used, for example, to "snap back" the knob to its rest or center position after the user lets go of the knob, e.g. once the knob is rotated past a particular position, a function is selected, and the user releases the knob to let the knob move back to its original position. An isometric rate-control mode for use with such a spring force is described below. A damping force sensation can also be provided on knob 54 to slow down the rotation of the knob, allowing more accurate control by the user. Furthermore, any of these force sensations can be combined together for a single knob 54 to provide multiple simultaneous force effects. Other forces usable with knob 54 are described in greater detail below with respect to Figure 9.

Knob 54 can similarly be provided directly on a radio, tuner, amplifier, or other electronic device, rather than on remote control 50. For example, a radio in a car that includes knob 54 can use force feedback "snap-to" detents for the favorite station frequencies preprogrammed by the user. This is convenient since the preferred radio frequencies are most likely spaced at irregular intervals in the radio frequency range; the ability to program the detents at any location in the range is desired. In addition, the knob can be moved by the actuators to select the nearest preprogrammed station, or a wide variety of different force sensations can be output. Furthermore, as described above, the detects can be used for different functions on the

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same knob, such as volume, tone, balance, etc. Alternatively, different sets of detent force profiles can be stored in a memory device on the radio and a particular set can be provided on the knob 54 by a microprocessor in the radio.

Figure 3b shows another embodiment in which a gamepad controller 60 is provided with a force feedback wheel. Controller 60 is intended to be held by both hands of a user. The controller 60 can include the standard input devices of game controllers, such as buttons 62, a directional game pad 64, and a fingertip joystick 66. The joystick 66 can in some embodiments be provided with force feedback. A finger wheel 68 can also be provided on controller 60 at any of various locations on the controller. Wheel 68 can operate similarly to the mouse wheel 16 described with reference to Figures 1 and 2, or to the knob 54 described with reference to Figure 3a. For example, wheel 68 can operate as a throttle or thrust control in a game for a simulated vehicle and include force feedback in an isometric mode or isotonic mode, or the wheel can be used to guide a pointer or other object on the screen.

FIGURE 4 is a block diagram illustrating an interface of the mouse system 30 of Figure 2 suitable for use with the present invention. Mouse system 30 includes a host computer 18 and interface device 31. A similar force feedback system including many of the below components is described in detail in U.S. patent nos. 5,734,373 and 5,825,308, which are incorporated by reference herein in their entirety.

Host computer 18 is preferably a personal computer, workstation, video game console, or other computing or display device, as explained with reference to Figure 1. Host computer system 18 commonly includes a host microprocessor 70, random access memory (RAM) 72, read-only memory (ROM) 74, a clock 78, and a display device 20. Host microprocessor 70 can include a variety of available microprocessors from Intel, AMD, Motorola, or other manufacturers. Microprocessor 108 can be single microprocessor chip, or can include multiple primary and/or co-processors. Microprocessor 108 preferably retrieves and stores instructions and other necessary data from RAM 72 and ROM 74 as is well known to those skilled in the art. In the described embodiment, host computer system 18 can receive sensor data or a sensor signal via a bus 80 from sensors of system 10 and other information. Microprocessor 70 can receive data from bus 120 using I/O electronics, and can use the I/O electronics to control other peripheral devices. Host computer system 18 can also output commands to interface device 31 via bus 120 to cause force feedback.

Clock 78 is a standard clock crystal or equivalent component which can be used by host computer 18 to provide timing to electrical signals used by host microprocessor 70 and other components of the computer system 18. Display device 20 is described with reference to Figure 1. Other types of peripherals can also be coupled to host processor 70, such as storage devices

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(hard disk drive, CD ROM drive, floppy disk drive, etc.), printers, audio output devices, and other input and output devices.

Interface device 31 is coupled to host computer system 18 by a bi-directional bus 120. The bi-directional bus sends signals in either direction between host computer system 18 and the interface device 104. Bus 120 can be a serial interface bus providing data according to a serial communication protocol, a parallel bus using a parallel protocol, or other types of buses. An interface port of host computer system 18 connects bus 120 to host computer system 18. In another embodiment, an additional bus can be included to communicate between host computer system 18 and interface device 11. One preferred serial interface bus used in the present invention is the Universal Serial Bus (USB). USB can also source power to drive actuators 64 and other devices of device 31.

The electronic portion of interface device 31 includes a local microprocessor 90, local clock 92, local memory 94, sensor interface 96, and actuator interface 98. Additional electronic components may also be included for communicating via standard protocols on bus 120. These components can be included in device 31 or host computer 18 if desired.

Local microprocessor 90 preferably coupled to bus 120 and is considered "local" to interface device 31, where "local" herein refers to processor 90 being a separate microprocessor from any processors 70 in host computer 18, and to processor 90 being dedicated to force feedback and sensor I/O of the interface device 31. Microprocessor 90 can be provided with software instructions to wait for commands or requests from host computer 18, parse/decode the command or request, and handle/control input and output signals according to the command or request. In addition, processor 90 preferably operates independently of host computer 18 by reading sensor signals and calculating appropriate forces from those sensor signals, time signals, and force processes selected in accordance with a host command, and output appropriate control signals to the actuators. Suitable microprocessors for use as local microprocessor 90 include the 8X930AX by Intel, the MC68HC711E9 by Motorola and the PIC16C74 by Microchip, for example. Microprocessor 90 can include one microprocessor chip, or multiple processors and/or co-processor chips, and can include digital signal processor (DSP) functionality. Also, "haptic accelerator" chips can be provided which are dedicated to calculating velocity, acceleration, and/or other force-related data.

For example, in one host-controlled embodiment that utilizes microprocessor 90, host computer 18 can provide low-level force commands over bus 120, which microprocessor 90 directly transmits to the actuators. In a different local control embodiment, host computer system 18 provides high level supervisory commands to microprocessor 90 over bus 120, and microprocessor 90 manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer 18. In the local control

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embodiment, the microprocessor 90 can independently process sensor signals to determine appropriate output actuator signals by following the instructions of a "force process" that may be stored in local memory and includes calculation instructions, formulas, force magnitudes, and/or other data. The force process can command distinct force sensations, such as vibrations, textures, jolts, or even simulated interactions between displayed objects. The host can send the local processor a spatial layout of objects in the graphical environment so that the microprocessor has a mapping of locations of graphical objects like enclosures and can determine interactions with the cursor locally. Such operation of local microprocessor in force feedback applications is described in greater detail in patent nos. 5,734,373 and 5,825,308. In an alternate embodiment, no local microprocessor 90 is included in interface device 31, and host computer 18 directly controls and processes all signals to and from the interface device 31.

A local clock 92 can be coupled to the microprocessor 90 to provide timing data, similar to system clock 78 of host computer 18 to, for example, compute forces to be output by actuators 106 and 112. In alternate embodiments using the USB communication interface, timing data for microprocessor 90 can be retrieved from the USB interface. Local memory 94, such as RAM and/or ROM, is preferably coupled to microprocessor 90 in interface device 31 to store instructions for microprocessor 90, temporary and other data, calibration parameters, adjustments to compensate for sensor variations can be included, and/or the state of the force feedback device.

Sensor interface 96 may optionally be included in device 31 to convert sensor signals to signals that can be interpreted by the microprocessor 90 and/or host computer system 18. For example, sensor interface 96 can receive signals from a digital sensor such as an encoder and convert the signals into a digital binary number. An analog to digital converter (ADC) can also be used. Such circuits, or equivalent circuits, are well known to those skilled in the art. Alternately, microprocessor 90 or host computer 18 can perform these interface functions. Actuator interface 98 can be optionally connected between the actuators 106 and 112 and microprocessor 90 to convert signals from microprocessor 90 into signals appropriate to drive the actuators. Interface 98 can include power amplifiers, switches, digital to analog controllers (DACs), and other components, as well known to those skilled in the art. In alternate embodiments, interface 98 circuitry can be provided within microprocessor 90 or in the actuators.

In a preferred embodiment, power is supplied to the actuators 106 and 112 and any other components (as required) by the USB. Alternatively, power from the USB can be stored and regulated by device 31 and thus used when needed to drive actuators 106 and 112. Or, a power supply can optionally be coupled to actuator interface 98 and/or actuators 106 and 112 to provide electrical power.

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A mechanical portion 100 is included in device 31 for the force feedback functionality of mouse 12. A suitable mechanical portion 100 is described in detail in co-pending PCT application WO 98/24183. A separate mechanical portion 102 is preferably provided for the force feedback functionality of wheel 16, as described in detail below with reference to Figures 5-8. In those embodiments not including force feedback in the planar mouse workspace (such as in Figure 1), the mechanical portion 100 need not be included. Furthermore, the embodiment of Figure 1 need not include a local microprocessor 90 or mechanical portion 100, where host computer 18 directly controls all forces on wheel 16.

Mechanical portion 100 preferably includes sensors 104, actuators 106, and mechanism 108. Sensors 104 sense the position, motion, and/or other characteristics of mouse 32 along one or more degrees of freedom and provide signals to microprocessor 90 including information representative of those characteristics. Typically, a sensor 104 is provided for each degree of freedom along which mouse 32 can be moved, or, a single compound sensor can be used for multiple degrees of freedom. For example, one sensor can be provided for each of two planar degrees of freedom of mouse 32. Examples of sensors suitable for embodiments described herein include optical encoders, analog sensors such as potentiometers, Hall effect magnetic sensors, optical sensors such as a lateral effect photo diodes, tachometers, and accelerometers. Furthermore, both absolute and relative sensors may be used.

Actuators 106 transmit forces to mouse 32 in one or more directions along one or more degrees of freedom in response to signals output by microprocessor 90 and/or host computer 18, i.e., they are "computer controlled." The actuators 106 produce "computer-modulated" forces which means that microprocessor 90, host computer 18, or other electronic device controls the application of the forces. Typically, an actuator 106 is provided for each degree of freedom along which forces are desired to be transmitted. Actuators 106 can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), voice coil actuators, etc. Passive actuators can also be used, including magnetic particle brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. In some embodiments, all or some of sensors 104 and actuators 106 can be included together as a sensor/actuator pair transducer.

Mechanism 108 is used to translate motion of mouse 32 to a form that can be read by sensors 104, and to transmit forces from actuators 106 to mouse 32. A preferred mechanism 108 is a closed-loop five-member linkage as described above in co-pending PCT application WO 98/24183. Other types of mechanisms can also be used, as disclosed in U.S. patent nos. 5,731,804; 5,767,839; 5,721,566; 5,805,140; and 5,691,898, all incorporated by reference herein. In the embodiment of Figure 1, mouse 12 typically has a ball and roller mechanism to sense the motion of the mouse, as is well known to those skilled in the art. User object 32 is preferably a

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mouse but can alternatively be a joystick, remote control, or other device or article, as described above.

Mechanical portion 102 interfaces the wheel 16 with the host computer 18. Portion 102 includes a sensor 110, an actuator 112, a mechanism 114, and wheel 16. Sensor 110 can be any suitable sensor for detecting the rotary motion of wheel 16, such as an optical encoder, potentiometer, or other varieties as described above for sensors 104. Alternatively, sensor 110 can be a linear sensor that senses linear motion of mechanism 114 converted from the rotary motion of wheel 16. Sensor 110 can be an absolute sensor, where absolute positions of the wheel in the range of motion are reported to host computer 18; or a relative sensor, in which changes in position from a previous position are reported to the host computer. Sensor 110 can be directly coupled to the user object 12 or 32, be coupled through a drive mechanism, or can be decoupled from the user object (e.g. by sensing motion using electromagnetic beam detectors and emitters).

Actuator 112 is any suitable actuator for providing rotary forces on wheel 16 and produces "computer-modulated" forces as referred to above similarly to actuators 106. In the preferred embodiment, actuator 112 is a DC current control motor that has a small enough size to fit into a small manipulandum such as a mouse and a small enough weight as to not interfere with mouse planar movement. Thus, the forces provided on wheel 16 may be small, but since the finger of a user is typically quite sensitive, small magnitude forces are sufficient to convey a variety of force sensations. In other embodiments, different types of active or passive actuators can be used as described above with reference to actuators 106. For example, passive actuators such as a magnetic particle brake, a friction brake, an electrorheological fluid actuator, or a magnetorheological fluid actuator, are quite suitable for use as actuator 112 due to their smaller size and weight and reduced power requirements. If such passive actuators are used, then a desired amount of play can be provided between actuator and wheel 16 to allow sensing of the wheel when the actuator is activated, as described in greater detail in patent nos. 5,721,566 and 5,767,839.

Also, a drive mechanism such as a capstan drive mechanism can be used to provide mechanical advantage to the forces output by actuator 112. Some examples of capstan drive mechanisms are described in patents 5,731,804 and 5,767,839. Alternatively, a belt drive system can be used as described below with reference to Figure 8.

In the described embodiment, the sensor 110 can input signals to a single sensor interface 96 used also for sensors 104 as described above. Actuator 112 can similarly use the actuator interface 98 also used by actuators 106. Alternatively, sensor 110 and/or actuator 112 can be provided with their own dedicated interfaces separate from interfaces 96 and 98.

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Mechanism 114 is provided to allows sensor 110 to sense the rotary motion of wheel 16 and to transmit rotary forces to the wheel 16 from actuator 112. Mechanism 114 can be a simple direct coupling of actuator 114 and sensor 112 to the wheel 16, as shown in Figures 5-6. Alternatively, a more complex mechanism can be used, such as a mechanism including a transmission system (e.g. a belt drive or capstan drive) as shown in Figures 7-8.

Other input devices 120 can be included in interface device 31 and send input signals to microprocessor 90 and/or host computer 18. Such input devices can include buttons, such as buttons 15 on mouse 12 or 32, used to supplement the input from the user to a GUI, game, simulation, etc. running on the host computer. Also, dials, switches, voice recognition hardware (e.g. a microphone, with software implemented by host 18), or other input mechanisms can be used. Furthermore, a safety or "deadman" switch can also be included to send a signal (or cease sending a signal) to microprocessor 90 and/or host 18 indicating that the user is not gripping the manipulandum 12 or 32, at which point the microprocessor 90 and/or host 18 commands the cessation of all output forces for safety purposes. Such safety switches are described in co-pending patent no. 5,691,898.

Furthermore, a safety switch 115 can be included for the wheel 16 to prevent forces from being output on the wheel when the user is not contacting or using it, and to prevent the wheel from spinning on its own when the user is not touching it. In one embodiment, the safety switch detects contact of a user's digit (finger, thumb, etc.) with the wheel. Such a switch can be implemented as a capacitive sensor or resistive sensor, the operation of which is well known to those skilled in the art. In a different embodiment, a switch or sensor that detects downward pressure on the wheel 16 can be used. For example, a switch can be sensitive to a predetermined amount of downward pressure, which will close the switch. A button switch for wheel 16 similar to that described below with reference to Figure 8, for example, can function as a safety switch. Or, a two-state switch can be used, where the first state is entered when a small amount of pressure is applied to wheel 16, functioning as the safety switch; and the second state is entered with a greater amount of pressure to activate a button switch and send a button signal. Alternatively, a pressure magnitude sensor can be used as the safety switch, where forces are output on the wheel only when a downward pressure magnitude over a minimum threshold is sensed. A pressure requirement for safety switch 115 has the advantage of ensuring good contact between finger and wheel before forces are output; output forces are enabled only when the user is moving or actively using the wheel. Thus, if the user simply rests his or her finger lightly on the wheel without intending to use it, no forces will be output to surprise the user.

FIGURE 5 is a perspective view of a first embodiment of the mechanical portion 102 for a force feedback wheel (e.g. mouse wheel or knob) including a direct drive mechanism. Sensor 110 and actuator 112 are grounded (schematically shown by ground 126), and mouse wheel 16 extends partially out of an aperture in the housing of mouse 12 or 32. Mouse wheel 16 is

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coupled to actuator 112 by a shaft 128; thus, when the actuator applies rotary force to shaft 128 about axis A, the user's finger 130 on wheel 16 will feel the rotary force about axis A. It should be noted that if the user is applying sufficient force in the opposite direction of the rotary force, the actuator operates in a stalled condition where the wheel 16 will not physically rotate, but the user will feel the rotational force.

Sensor 110 is coupled to the shaft 128 (or a portion of actuator 112 coupled to shaft 128) to measure the rotation of the shaft about axis A and thus the rotation of the wheel 16. Sensor 110 senses the rotation of wheel 16 even when no forces are applied to the wheel by actuator 112. In the embodiment of Figure 5, the actuator 112 is provided between the sensor 110 and the wheel 16. FIGURE 6 is a perspective view of a second embodiment 102' of mechanical portion 102, where the wheel 16 is positioned between the sensor 110 and actuator 112. Embodiment 102' is more appropriate than embodiment 102 when a desired play is introduced between actuator and wheel 16, since the sensor is desired to be rigidly coupled to wheel 16 without play in such an embodiment. In other respects, the embodiment 102' functions similarly to the mechanical portion 102.

FIGURE 7 is a perspective view of a third embodiment 102'' of mechanical portion 102 for force feedback mouse wheel 16. Wheel 16 is coupled to a pulley 132 by a rotatable shaft 134, where pulley 132, shaft 134, and wheel 16 rotate about axis B. In this embodiment, the pulley 132, shaft 134, and wheel 16 are preferably fixed at their rotation location, i.e., axis B is fixed with respect to mouse 12 or 32. Pulley 132 is coupled to a pulley 136 by a belt 138. Pulley 136 is rigidly coupled to a shaft 140, which is coupled to actuator 112 and to sensor 110, where pulley 136, actuator 112, and sensor 110 rotate about axis C. Mechanical portion 102'' thus operates similarly to the embodiment 102, except that the belt transmission system 142 that includes pulley 132, belt 138, and pulley 134 is used to scale the motion of wheel 16 and forces applied to wheel 16. For example, pulley 136 preferably has a smaller diameter than pulley 132 to allow the rotational motion of wheel 16 to be converted to a greater number of rotations of shaft 140, thus increasing the sensing resolution. Furthermore, a smaller rotation of shaft 140 translates to a greater amount of rotation of shaft 134, thus providing mechanical advantage to forces output by actuator 112 and allowing a smaller actuator to be used in mouse 12 or 32. In other embodiments, belt 138 can be a cable, or belt transmission system 142 can be a capstan drive system. Other mechanical transmission systems may also be used.

FIGURE 8 is a perspective view of a fourth embodiment 102''' of mechanical portion 102 for force feedback mouse wheel 16. Embodiment 102''' is similar to embodiment 102'' except that axis B is floating, i.e., may be rotated about axis C. Thus, the assembly including pulley 132, shaft 134, and wheel 16 may be rotated about axis C. This motion allows the wheel 16 to move approximately vertically with reference to the horizontal planar orientation of the

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mouse 12 or 32, as indicated by arrow 144. The wheel thus may be pushed down by the user into the housing of the mouse 12 or 32 like a button.

Spring contacts 146a and 146b are preferably provided in the path of the wheel 16. Contacts 146a and 146b each include a moving portion 148 that is forced toward a grounded portion 150 when the moving shaft 134 engages moving portions 148. A spring 152 is provided between each of the grounded and moving portions 150 and 148. When the moving portion 148 has been moved down enough to contact the grounded portion 150, a circuit is closed and a signal is sent to the microprocessor 90 and/or host computer 18 indicating that the wheel 16 has been pressed. The software running on the host computer can interpret the wheel-press signal to perform an associated task or process. When the user removes his or her finger from wheel 16, springs 152 force the moving portions 148 and the wheel 16 back to their original position. Other equivalent mechanisms may also be used in other embodiments to allow the wheel 16 to function as a button in addition to its rotational function. Furthermore, the contacts 146 can be used as a safety switch in some embodiments, as described above.

FIGURE 9 is a diagrammatic view of display screen 20 of host computer 18 displaying a graphical environment for use with the present invention. In the described example, a GUI 200 displays a window 202 on display screen 20. A cursor or pointer 204 is a user controlled graphical object that is moved in conjunction with the mouse 12 or 32 in its planar workspace.

The force feedback wheel 16 of the present invention can be used to control and/or enhance functions of the GUI 200. A normal mouse wheel can be used to scroll a document or view of the GUI, zoom a view, or pan a view by rotating the mouse wheel. In the present invention, several types of force sensations can be output on wheel 16 to enhance control or selection in the GUI of these types of rate-control functions. Any of the described force sensations can be combined on wheel 16 to provide multiple simultaneous force effects where appropriate.

One feature of the force feedback wheel is force detents. As described above with reference to Figure 3a, force detents are forces that attract the wheel to a particular rotational position and resist movement of the wheel away from that position, e.g. a "snap-to" detent. The detents can be programmable by an application developer or other designer/user to correspond with particular features of the GUI 200. For example, the host computer can send a high-level host command to the interface device 31 (e.g. microprocessor 90), where the host command has a command identifier and command parameters. The identifier (such as "WHEEL_DETENT") identifies the command as a force detent command, while the parameters characterize the detent forces. For example, parameters such as "θ angle of detent" and "magnitude" can be used, so that a command WHEEL_DETENT (θ, magnitude) characterizes a detent. A command of WHEEL_DETENT (20, 10) would command a wheel detent at an angle of 20 degrees on the

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wheel from a reference position (when viewing wheel coincident with axis of rotation), at a force magnitude of 10% of maximum force output (magnitude can also be expressed in other terms). Additional angle parameters can define additional detents located at different angles around the wheel in a range of 360 degrees, irregularly or regularly spaced as desired. Alternatively, "N pulses per revolution" can be a parameter to command N regularly-spaced force detents per revolution of the wheel. If a local microprocessor 90 is used, the microprocessor can implement the detents independently of control of the host based on the received host command.

For example, one standard GUI feature is a pull-down menu 206. Individual menu items 208 in the pull down menu 206 may be selected by the user using cursor 204. Once the pull-down menu has been displayed, the selection of a menu item 208 can be controlled by wheel 16 moving cursor 204 (and, optionally, vertical motion of mouse 12 or 32 can be disabled while the menu is displayed). For example, a menu item selection bar 209 (or highlighter) can be moved up or down menu 206 by rotating the wheel 16. The force detents can be output on wheel 16 to correspond with the spacing of menu items 208. Thus, the selection of a menu item is made easier from the use of detent forces, which substantially reduces the tendency of the user to overshoot a menu item when moving a cursor down the list of menu items. Furthermore, since the force detents are programmable, the user or software developer can set a rotational distance between detents to a particular preference, and can also set the magnitude of detent forces, e.g. for the "depth" of the detent which controls how easily the user may move the wheel past or out of a detent.

Detent forces can similarly be used for other GUI or application program features. For example, the spacing of objects on a document can be synchronized with force detents. As the document is scrolled using wheel 15, each time a particular object is scrolled past a predetermined location in a window, a force detent can be output. For example the spacing of lines 214 of text in a text document 212 can be synchronized with force detents so that if these text lines are scrolled by the cursor or other location in the window using the wheel 16, a force detent is output on the wheel 16. Similarly, the grid spacing on a spreadsheet or the links on a web page can be associated with force detents. The force detents can be spaced to correspond with the spacing of the text or other features to provide the user with greater feedback concerning the graphical features. Thus, a text document having single-spaced lines would cause force detents to be output in quick succession as the document is scrolled, while a text document having double-spaced lines would cause force detents to be output twice the rotational distance apart as the single spaced document. In other embodiments in which the wheel 16 is used to position the cursor 204 (described below), force detents can be output on wheel 16 when the cursor is moved over a particular graphical object, such as a text word, an icon, or a menu item 208. The flexibility of characterizing the computer-controlled actuator force detents makes

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these detents far more helpful to a user than the static mechanical detents provided in mouse wheels of the prior art.

A different force sensation which can be output on wheel 16 is a spring force or spring return force. Similarly to the knob 54 described with reference to Figure 3a, the spring return force resists rotational motion of the wheel away from a "rest position", where the magnitude of the spring force is proportional to the distance the wheel is rotated away from the rest position. This force can cause the wheel to spring back to its rest position when the user releases the wheel. A host command such as WHEEL_SPRING (state, stiffness) can be sent to the interface device 31 to characterize the spring return force, where the state ("ON" or "OFF") turns the spring force on or off and the stiffness indicates the magnitude of spring force output on the wheel. Also, additional parameters to characterize the spring can be included in the command, such as +k and –k (spring constant and direction), dB (deadband area around designated position in which no forces are applied), and +Sat, -Sat (saturation level over which the magnitude is not increased).

Such a spring force can be useful, for example, for isometric scrolling of a document or view in GUI 200. Isometric scrolling allows the user to exert pressure to control the direction and/or speed of scrolling or other rate control tasks. Isometric scrolling can be approximated through the use of a spring force, where the user exerts a force on the wheel 16 to rotate the wheel, but the spring force resists such a user force. The speed of scrolling is based on the distance of compression of the simulated spring. For example, the further the user pushes the wheel against the spring force, the faster a document will scroll. When the user releases the wheel, the actuators move the wheel back to its rest position (or the wheel is left in its current position) and the document stops scrolling. Alternatively, the user might wish to set preferences so that the document continues to scroll even when the wheel is released, where the activation of a different command or control stops the scrolling. In a different embodiment, the distance of a scrolling window or view can be based on the distance of compression of the simulated spring in a position control paradigm. For example, a document or a first-person view in a game can scroll based directly on the amount of rotation of the wheel against the spring force; when the user releases the wheel, the spring force moves both the wheel and the document or view back to the rest position. In a different embodiment, a spring return force can be used on wheel 16 when the wheel is used to control thrust or velocity of a simulated vehicle or character in a game. Or, the spring return force can be used in conjunction with zooming or panning functions in a GUI, game, or other graphical environment.

Another force sensation that can be used with wheel 16 is a jolt or pop force sensation. For example, a jolt can be command with a command such as WHEEL_JOLT(magnitude, duration), which characterizes the magnitude of the jolt force and its duration. Such jolts can be used to indicate to the user that designated objects have scrolled past a particular location on the

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screen. For example, each time a page break in a text document scrolls by the cursor 204 or scrolls past the bottom of the displayed window, a jolt can be output on wheel 16. Other objects such as web page links, images, etc. can also be associated with jolts. A jolt differs from a detent in that a jolt is time-based rather than spatially based; the jolt is output irrespective of the position of the wheel 16, and does not attract or repel the wheel from a particular rotational position.

A different force sensation that can be output on wheel 16 is a vibration. Like the jolt force, this type of force "effect" is time based, not based on the rotational position of the wheel. The vibration force can be commanded with a command such as WHEEL_VIBRATION (Frequency, Waveform, Magnitude) to characterize the vibration force, where "Waveform" can be a sine wave, square wave, triangle wave, or other-shaped wave. The vibration can be associated with particular graphical objects displayed on the screen, or be output based on events that occur in a host application. For example, a vibration can be output on wheel 16 when a warning or alert message is given, such as when the user receives new mail or when an error in a program occurs.

Other force sensations that can be output on wheel 16 are inertia, friction, and/or damping force. An inertia force is based on a simulated mass of an object, where the larger the mass, the greater the force resisting motion of the object. For example, a document can be assigned a simulated mass based on a characteristic of the document, such as the file size of the document, the font used in the document, etc. A document having a larger mass has a greater inertia force associated with it, so that the wheel 16 is more difficult to rotate when scrolling a large document as compared to scrolling a smaller document. The user can perceive the force on the wheel 16 and readily discern the size of the scrolled document. A friction force depends on a predefined coefficient of friction which causes a drag force on the user manipulandum. A damping force sensation is based on the velocity of an object, where the greater the velocity, the greater the damping force. This force feels like resistance to motion through a viscous liquid. The faster wheel 16 is rotated, the greater the damping force on the wheel. This can be used, for example, to provide areas of a document where scrolling is desired to be slower or controlled to a more fine degree, or to alert the user of a particular portion of the document as it scrolls by.

Another use for wheel 16 is for "coupled control." Coupled control refers to the position of cursor 204 on screen 20 being controlled both by the position of mouse 12 or 32 in its planar workspace as well as by the rotational position of wheel 16 about its axis. In one embodiment, the Y (vertical) screen coordinate of the cursor 204 is determined by the Y position of the mouse added to the Y position of the wheel 16, as summarized by the following:

$$Y_{CURSOR} = Y_{MOUSE} + Y_{WHEEL}$$

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Thus, the user can move the cursor 204 in a Y-direction on the screen by moving mouse 12 or 32 in a Y-direction in its workspace, and/or by rotating wheel 16 (where wheel 16 is preferably oriented in the Y-direction so that it rotates about an axis parallel to the plane of mouse movement and oriented in the X-direction). If the user wishes to move the cursor 204 only with the wheel 16, the mouse 12 or 32 can be kept stationary within its workspace; if the user wishes to move the cursor only with the mouse, the wheel is not moved. Furthermore, if a wheel is provided on mouse 12 or 32 for horizontal (X-direction) motion, the X position of the cursor 204 can be determined from both the X-direction of the mouse 12 or 32 in its workspace and by the rotational position of the X-oriented wheel. In other embodiments, the position control of cursor 204 by mouse 12 or 32 can be disabled at selected times to allow wheel 16 to have exclusive control of the cursor 204 position. For example, when a pull down menu 206 is selected by the user, the Y position of the mouse 12 or 32 can be ignored to allow the wheel 16 to exclusively control the Y position of the cursor 204 as the user is selecting a menu item 208 in the menu 206. One analogy to such dual mouse-wheel cursor control is a "reel metaphor", in which the wheel can be considered a reel of rigid string (or controlling the length of a telescoping pole), where the reel is positioned on the mouse 12 or 32 and the cursor 204 is attached to the end of the string (or pole). Assuming the string is fully wound on the reel (or pole is fully contracted), the mouse controls the position of the cursor directly. When the wheel is moved and the string unwound (or pole is expanded), the cursor has additional movement beyond the motion controlled by the mouse. The user can push or pull on graphical objects by winding or unwinding the reel, and feel the appropriate forces from such actions through the wheel 16.

When force feedback wheel 16 is used to control the position of cursor 204, force sensations can provide enhanced control and tactile information to the user. For example, when the user moves the cursor 204 against a graphical object designated as a wall or other obstruction using wheel 16, a wall force can be output on the wheel 16 to resist further motion of the wheel and cursor into the wall. One way to implement such a wall is to output a spring force on the wheel, calculated as $F_Y = K\Delta Y_{CURSOR}$, where K is a spring constant and ΔY_{CURSOR} is the distance of penetration of the cursor into the wall surface along the Y axis resulting from the sum of both wheel Y motion and mouse Y motion. To make the wall seem like it is impassable, the cursor is preferably continued to be displayed against the wall surface even as the wheel 16 is rotated to penetrate the wall spring force, providing a breaking of the mapping between cursor and physical manipulandum in a position control paradigm.

Other force sensations can also be output on wheel 16 when the wheel controls the position of the cursor. For example, a texture force can be output on the wheel when the cursor is moved over a textured region or object. Examples of textures include a bumpy surface and a slick icy surface. Alternatively, spring forces, damping forces, inertia forces, frictional forces, barrier forces, ramping effect forces, or dynamic effects can all be output on the wheel 16 and

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associated with the motion of the cursor and/or the interaction of the cursor with other graphical objects in GUI 200. Also, one or more of these forces can be combined with one or more other forces to create compound force sensations on wheel 16.

Furthermore, force profiles may be used to control the forces on wheel 16. Force profiles are sequences of individual force magnitudes that have been stored in a storage device such as local memory 92, host RAM 74, a hard disk drive, floppy disk, CD-R or CD Rewritable, DVD, or other storage device. The force magnitudes can be output by microprocessor 90 to the actuator 112 in sequence to apply a particular force sensation characterized by the force profile. The microprocessor can output the force profile magnitudes (or a subset thereof) at different rates or with different offsets from the stored magnitudes as commanded by host computer 18 and/or as a function of characteristics, such as wheel velocity/acceleration/current position, time, etc.

The force feedback functionality of wheel 16 described above can also be provided in different modes of the interface device 12 or 31, where the user, microprocessor 90, and/or host computer 18 can control which mode is currently active. Examples of two preferred modes are isotonic mode and isometric mode. Example of similar isometric and isotonic modes for mouse 12 or 32 are also described in U.S. Patent No. 5,825,308.

Isotonic mode is a position control mode for wheel 16, where the forces output on the wheel are synchronized or associated with the position of the wheel, and where the position of the wheel, when changed, incrementally changes the position or state of a graphical object provided by the host computer. For example, when a position control scrolling is provided by wheel 16, a document is scrolled by an amount corresponding to the amount the wheel is rotated. Similarly, the coupled control described above is a position control function, since a cursor is incrementally moved based on incremental rotations of the wheel 16.

Force sensations that are appropriate for such a position control wheel mode include force detents. For example, as explained above, force detents are output on the wheel depending on when text lines or spread sheet cells are scrolled by, where each detent is incrementally output as a document is scrolled, zoomed, panned, etc. Damping, friction, and inertia forces are also position control mode forces, where the force depends on the velocity (which is position based) or the position of the wheel and the cursor, document, or other object which is directly controlled by the wheel. Obstruction forces which represent hard stops to the wheel can be used in position control mode to represent the end of travel of the wheel; for example, when the end of a document is reached during a scrolling function, a hard stop force can be output to indicate this condition and resist further scrolling. Alternatively, a wall obstruction force on wheel 16 indicates that a wheel-controlled cursor has hit a wall. Texture forces are also appropriate in the position control mode, where the texture force is dependent on the position of the wheel; for

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example, in the coupled control embodiment where the wheel influences the position of the cursor, texture bump forces corresponding to bumps on the screen can be output on the wheel as the cursor moves over the bumps.

Isometric mode (or "pressure" mode) is a rate control mode for wheel 16. The distance of the wheel from a particular position controls a rate of a computer function, such as the rate of scrolling, zooming or panning, the rate of fast-forwarding/rewinding a computer-displayed movie, the rate of travel of a simulated vehicle, the rate of change for frequencies to increase when selecting radio stations, etc. An appropriate force sensation to use for such an isometric mode is the spring return force, which biases the wheel to center itself back at a starting or center position. The user feels the spring force get stronger the more the wheel is rotated from the center position, and this accordingly controls the rate of the computer function, e.g. the speed of scrolling. Detent forces can also be used in isometric mode, e.g. in conjunction with a spring return force. For example, the detents do not indicate an increment of wheel motion, but indicate the rate settings, making their selection easier for the user. Thus, a user might program three favored speed settings for the wheel in isometric mode, where the settings are indicated as force detents when the wheel is rotated to those speed settings, thereby assisting the user in finding and maintaining the wheel at those settings. In addition, jolt, vibration, or other time based forces can also be output on wheel 16 in an isometric mode, for example, to indicate events such as a page break scrolling by or the status of a simulated engine in a controlled simulated vehicle upon reaching a certain velocity.

The isotonic and/or isometric modes can be selected in a variety of ways. For example, when a button 15 is held down by the user, an isometric mode can be entered at the current location of the cursor or current displayed region of a document. When the button is released, isotonic mode can be entered. Alternatively, isometric mode can be activated when the cursor moves against an "isometric surface", as described below. Other modes can also be selected using buttons 15 or other input devices. For example, when a "cursor mode" of wheel 16 is selected, the wheel 16 can control cursor movement as explained above. When the cursor mode is inactive, the wheel 16 can control scrolling, zooming, or panning of a document/view, or other functions. Force feedback output on the wheel 16 is appropriate to the currently-selected mode. The modes can be selected by host computer 18, microprocessor 90, or the user in other ways in other embodiments.

Other modes can also be implemented for wheel 16. One type of mode is a "force functionality mode." For example, a thumb button (not shown) or other button 15 can toggle the force functionality mode in which designated graphical objects or regions displayed on screen 20 have other functions enabled by force feedback. A graphical object, such as a window or icon in a GUI, can act differently for selection of functions of the host computer or program, and/or for the forces associated with the object/region, depending on whether the force functionality mode

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is active. For example, when the mode is not active, the cursor can be moved normally through the border or edge of a window, with no force sensations associated with the movement over the window. However, when the force mode is active (such as by pressing or holding a particular button 15), a spring force will be output on mouse 32 and/or on wheel 16 opposing the movement of the cursor through the window border, i.e. the window border becomes an "isometric surface." This force is used as for "pressure scrolling" or as a "scroll surface", where the amount of penetration of the mouse against the spring force controls the speed of scrolling, zooming, etc. of a document displayed in that window (similar to isometric mode described above). In a "pressure clicking" or "click surface" embodiment, if the cursor is moved against the border of an icon or other object and the force functionality mode is active, a force will be output resisting motion of the cursor into the icon; when the mouse 32 and/or wheel 16 moves against the force a threshold distance, the icon is selected as if the cursor had clicked or double-clicked on the icon. These types of features are especially applicable to wheel 16 when in the coupled cursor control embodiment described above. In other embodiments, other input devices besides or in addition to buttons 15 can control the force functionality mode. Or, different input devices can control different modes.

FIGURE 10 illustrates an application for a control knob embodiment of the present invention. A control panel 212 is provided for a device 210 and includes a control knob of the present invention. In the described embodiment, device 210 is an audio device that controls the output of sound, such as music or speech, from speakers that are connected to the device 210. For example, a common embodiment of device 210 is a stereo system that includes the ability to play sound from one or more media or signals, such as cassette tapes, digital audio transmission (DAT) tapes, compact discs (CD's) or other optical discs, or radio signals transmitted through the air from a broadcasting station.

The device 210 can also include additional or other functionality not related to audio control and output. For example, many vehicles include electronic systems to control the temperature in the vehicle cabin (air conditioning, heat, etc.), as well as systems to provide information on the current operating characteristics of the vehicle, such as current speed, engine temperature, fuel or other fluid levels, whether windows of the vehicle are open, etc. Other systems may include a navigation system that displays a map and the current location of the vehicle with respect to the map, a cellular telephone or other portable telephone control system, and a security/alarm system. Device 210 can include the ability to display information from and/or influence such other systems in a vehicle or other environment, such as a house, office, etc.

Alternatively, device 210 can be a variety of other electronic or computer devices. For example, device 210 can be a home appliance such as a television set, a microwave oven or other kitchen appliances, a washer or dryer, a home stereo component or system, a home computer, a

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set top box for a television, a video game console, a remote control for any device, a controller or interface device for a personal computer or console games, a home automation system (to control such devices as lights, garage doors, locks, appliances, etc.), a telephone, photocopier, control device for remotely-controlled devices such as model vehicles, toys, a video or film editing or playback system, etc. Device 210 can be physically coupled to the control panel 212, or the panel 212 can be physically remote from the device 210 and communicate with the device using signals transferred through wires, cables, wireless transmitter/receiver, etc.

Device 210 preferably includes a front panel 212, a display 214, several control buttons 216, and one or more control knobs 218 of the present invention. Front panel 212 can be mounted, for example, on the interior of a vehicle, such as on or below the dashboard, or in some other convenient area. Alternatively, the front panel 212 can be the surface of the external housing of the device 210 itself, such as a stereo unit. The device 210 may include several functions, such as playing an audio track, adjusting volume, tone, or balance of an audio output, displaying an image (icons, a map, etc.), or adjusting the temperature or fan speed in a vehicle, which can be changed or set by the user manipulating the controls of the device 210 on front panel 212.

Display 214 is provided to show information to the user regarding the controlled device or system and/or other systems connected to the device 210. For example, options 220 can be displayed to indicate which function of the device 210 is currently selected. Such options can include "radio," "tape," "CD,", or power, as shown. Other information, such as the current radio frequency 222 selected for a radio tuner, can also be displayed. Furthermore, any information related to additional functionality of the device 210 can also be displayed. For example, information 224 can be provided to allow the user to select one or more functions not related to the audio operation of the device 210. In some embodiments, a map or similar graphical display can be shown on display 214 of an device 10 to allow the user to navigate. Some examples of functions displayed by a display 214 are shown with respect to Fig. 2, below. In other embodiments, display 214 can be a separate monitor displaying a graphical user interface or other graphical environment as controlled by a host computer. Display 214 can be any suitable display device, such as an LED display, LCD display, gas plasma display, CRT, or other device. In some embodiments, display 214 can include a touch-sensitive surface to allow a user to touch displayed images directly on the display 214 to select those images and an associated setting or function.

Control buttons 216 are often provided on device 210 to allow the user to select different functions or settings of the device. For example, on an audio device, buttons 216 can include radio station preset buttons, rewind/fast forward tape functions, power, speaker loudness, etc. Virtually any function of the device can be assigned to buttons 216. The buttons 216 may also be used in conjunction with the control knobs 218, as described below.

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Control knobs 218 are provided to allow the user a different type of control of functions and settings of device 210 than the buttons 216 allow. Knobs 218, in the described embodiment, are approximately cylindrical objects engageable by the user. The knobs 218 can alternatively be implemented as a variety of different objects, including conical shapes, spherical shapes, dials, cubical shapes, rods, etc., and may have a variety of different textures on their circumferential surfaces, including bumps, lines, or other grips, or even projections or members extending from the circumferential surface. In addition, any of variety of differently-sized knobs can be provided; for example, if high-magnitude forces are output, a larger-diameter cylindrical knob is often easier for a user to interface with device 210. In the described embodiment, each knob 218 rotates in a single rotary degree of freedom about an axis extending out of the knob, such as axis A. The user preferably grips or contacts the circumferential surface 226 of the knob 218 and rotates it a desired amount. Force feedback can be provided in this rotary degree of freedom in some embodiments, as described in greater detail with reference to Figs. 12a and 12b.

Furthermore, the control knobs 218 of the present invention allow additional control functionality for the user. The knobs 218 are preferably able to be moved by the user in one or more directions approximately perpendicular to the axis A of rotation, e.g. parallel to the surface of the front panel 212 as shown in Fig. 10 ("transverse motion" or "transverse direction"). This transverse motion is indicated by arrows 228. For example, the knob 218 can be moved in the four orthogonal directions shown, or may be moveable in less or more directions in other embodiments, e.g. only two of the directions shown, or in eight directions spaced at 45 degree intervals about axis A. In one embodiment, each transverse direction of the knob is spring loaded such that, after being moved in a direction 228 and once the user releases or stops exerting sufficient force on the knob, the knob will move back to its centered rest position. In other embodiments, the knob can be provided without such a spring bias so that the knob 218 stays in any position to which it is moved until the user actively moves it to a new position.

This transverse motion of knob 218 can allow the user to select additional settings or functions of the device 210. In some embodiments, the additional control options provided by knob 218 allow the number of buttons 216 and other controls to be reduced, since the functions normally assigned to these buttons can be assigned to the knob 218. For example, the user can move a cursor 30 or other visual indicator on display 214 (e.g. pointer, selection box, arrow, or highlighting of selected text/image) to a desired selection on the display. Thus, the cursor 230 can be moved from the "radio" selection shown to the "tape" selection by moving the knob 218 in the down direction as shown in Fig. 10. Or, the cursor 230 can be moved to the "CD" selection by moving the knob 218 in the direction to the right. If knob 218 is provided with diagonal directions (e.g. at 45 degree intervals), the user can move the cursor 230 from the "radio" selection directly to the "off" selection. The user can similarly move cursor 230 or a

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different indicator to the other information settings 224, to the frequency display 222, or to any other displayed option, setting, or area/region on the display 214.

Besides such a cursor positioning mode, the transverse motion of knob 218 can also directly control values or magnitudes of settings. For example, the left motion of knob 218 can decrease the radio station frequency value 222, where the value can decrease at a predetermined rate if the user continually holds the knob 218 in the left direction. The right motion of the knob 218 can similarly increase the frequency value 222. In another example, once one of the information settings 24 is selected, a sub menu can be displayed and the directions 228 of knob 218 can adjust air temperature, a timer, a cursor on a displayed map, etc.

Different modes can also be implemented; for example, the default mode allows the user to control cursor 230 using the directions 228 of the knob. Once the cursor is located at a desired setting, such as the frequency value 222, the user can switch the mode to allow the directions 28 to control the setting itself, such as adjusting the value 222. To switch modes, any suitable control can be used. For example, the user can push a button, such as button 229, to toggle a mode. Alternatively, the user can push or pull the knob 218 to select the mode; this functionality of the present invention is described below. Or, some or all of the directions 228 can be used to select modes; for example, the down direction might switch to "volume" mode to allow the user to rotate the knob to adjust volume; the up direction can switch to "adjust radio frequency" mode, and the left direction can switch to "balance" mode (for adjusting the speaker stereo balance for audio output with rotation of knob 218).

In addition, the control knobs 218 are preferably able to be pushed and/or pulled in a degree of freedom along axis A (or approximately parallel to axis A). This provides the user with additional ways to select functions or settings without having to remove his or her grip from the knob. For example, in one preferred embodiment, the user can move cursor 230 or other indicator on the display 214 using the directions 228 of the knob 218; when the cursor has been moved to a desired setting or area on the display, the user can push the knob 218 to select the desired setting, much like a mouse button selects an icon in a graphical user interface of a computer. Or, the push or pull function can be useful to control the modes discussed above, since the user can simply push the knob and rotate or move the knob while it is in the pushed mode, then release or move back the knob to select the other mode. The modes discussed above can also be toggled by pushing or pulling the knob 218. The push and/or pull functionality of the knob 218 can be provided with a spring return bias, so that the knob returns to its rest position after the user releases the knob. Alternatively, the knob can be implemented to remain at a pushed or pulled position until the user actively moves the knob to a new position.

A slider control 232 of the present invention may also be included in device 210. Slider control 232 includes a slider knob 234 which is grasped by the user and moved in a linear

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direction as shown by arrow 236. In the present invention, slider control 232 preferably includes force feedback functionality. Thus, as the user moves the knob 234, force sensations such as a spring force, a damping force, jolts, detents, textures, or other forces can be output and felt by the user. Furthermore, the slider knob 234 can include a button 238 which can be pressed by the user similarly to the push knob embodiment discussed above with reference to knob 218. Alternatively, the knob 234 can be pushed and/or pulled similarly to the knob 218 as described above. Slider control 232 can control any of the various functions, settings, or options of the device 210. For example, the motion left or right of knob 234 can control the radio frequency 222, where force detents are output for each station and/or each preset station previously programmed by the user. Or, the cursor 230 can be moved using the slider knob 234, such that when the cursor reaches a desired setting or selection, the user can push button 238 or push on the knob 234 to select that setting. Other functions such as volume, balance, tone, map functions, temperature functions, or mode selection can also be controlled by the slider control 232. Slider control is described in greater detail with respect to Figure 14.

FIGURE 11 is an example showing images which can be displayed on display 214 to assist the user in selecting options with knobs 218 and/or slider control 232. Display 214 can present icons as shown, in this example for the control of audio output signals from device 210. Icon 246 is selected to control the volume of the audio output using knob 218, where the circular pointer 242 can be moved in accordance with the knob 218. Icon 247 is used to control the frequency of the radio tuner (the current selected frequency can be displayed as well), and the icons 248, 249, and 251 are used to control the balance, treble, and bass of the audio, respectively. For example, the indicator 244 can be moved left or right depending on the current setting. Cursor 245 is used to select one of the icons to allow the control of the functions associated with the selected icon. Cursor 245 indicates which of the icons in display 214 are currently selected. The icon can be moved from each icon to the next by rotating the knob 218. Alternatively, the transverse motion of the knob can move the cursor 245. A function of the device designed by the selected icon can be selected by pushing the knob 218 in the linear direction. The cursor can be a square or other-shaped box, or the currently-selected icon can be highlighted to indicate the cursor's location.

It should be noted that each of the icons can preferably be set to a position control mode or to a rate control mode as desired by the user. For example, the user may select position control for volume 246 and rate control for the functions of icons 247, 248, 249, and 251, or any other combination. In position control mode, force detents are preferably output to indicate particular settings or how far the knob 218 has been rotated. In rate control mode, detents can also be output. For example, the user maintains the knob 218 at a rotary position away from the center position in opposition to a spring return force, and a detent force (e.g., jolt) is output to indicate how much a particular value has been changed. For example, a jolt can be output for

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each 10 MHz of frequency that is increased, or for each particular amount of treble or bass that has been adjusted.

Other icons can be displayed in other embodiments. For example, an for vent location can be selected using cursor 245 to determine which vents in the car provide air flow, where a top vent, a bottom vent, or both top and bottom vents can be selected. A fan speed icon can be selected to choose a fan speed setting for the air flow from the vents in the car. In a preferred force feedback implementation, once the fan speed icon has been selected by pushing in the knob 218, the user may rotate the knob 218 to select the fan rotation speed in a position control mode. A small vibration can be output on the knob 218 in the rotary degree of freedom, where the frequency (or magnitude) of the vibration forces correlate with the magnitude of fan rotation speed, i.e., a high fan speed provides a fast vibration. Furthermore, detents are preferably output superimposed on the vibration forces so that the user can feel the fan settings at the detents. This allows the user to select fan speed based purely on tactile feel, so that the driver need not look at the display 214. A temperature icon can be selected to adjust the temperature in the car. The temperature can preferably be adjusted by rotating knob 218, where force detents indicate each temperature setting. Icons for moving mechanical components, such as seats or mirrors, can be provided, where a rate control force mode is used to control the position of the components.

FIGURE 12a is a perspective view and FIGURE 12b is a side elevational view of one implementation of control knob 218 of the present invention. In this implementation, knob 218 includes the ability to move transversely in four directions, and the knob 218 can also be pushed for additional selection ability.

Knob 218 is rigidly coupled to a rotatable shaft 250 which extends through the grounded front panel 212 (shown in dashed lines). Shaft 250 extends through a four-way switch 252 which detects the transverse motion of the knob 218 in directions 228. The knob 218 is biased toward the centered rest position within switch 252 by a spring member 264, described in greater detail below. When the shaft 250 is moved in any of the provided transverse directions, a corresponding micro switch (not shown) included on the interior sidewall of the four-way switch 52 is closed, thus causing a signal to be output on leads 254. Thus, switch 252 preferably includes individual micro switches, one for each provided transverse direction (four individual switches in the described embodiment). A suitable switch for use as switch 252 is a "hat switch" which is commonly provided for analog joystick controllers for personal computers and allows 4 or 8 directions to a moveable member. For example, joystick hat switches manufactured by such companies as CH Products, Inc. or Logitech can be used. In other embodiments, two-way, eight-way, or other types of switches can be used, depending on how many directions are desired.

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A pusher member 256 is rigidly coupled to shaft 250 next to the switch 252. Since the switch 252 includes an aperture through which the shaft 250 extends, the knob 218, shaft 250 and pusher member 256 are operative to move as a unit along axis A with respect to the front panel (ground) and the switch 252. A switch 258 (see Fig. 12b) is coupled to a grounded member 260 and is provided in the path of the pusher member 256. Thus, when the knob 218 is pushed by the user, the shaft 250 and the pusher member 256 are moved along axis A in a direction indicated by arrow 262 (see Fig. 12b). This causes pusher member 256 to engage the button 264 of the switch 258, causing the button 264 to be pushed inward and close (or open) the switch. The pushing motion of the knob 218 is thus sensed.

In other embodiments, a sensor can be provided to sense a range of positions of the knob 218 or a continuous motion of the knob 218 linearly along axis A. For example, a Hall effect switch can be provided on pusher member 256 which measures the position of the pusher member 256 relative to a grounded magnet on member 260 (or the Hall effect switch can be placed on the member 260 and the magnet can be placed on the member 256). Or, an optical sensor (such as a photodiode) or other type of sensor can detect the position of the member 256 and/or knob 218. In such an embodiment, the position of the knob along axis A can proportionately control a function or setting of the device 210. For example, such movement can control the volume of audio output of the device, motion of a cursor across a display, or the brightness of lights inside a vehicle.

A pull switch can be implemented similarly to the push switch shown in Figs. 12a and 12b. For example, a switch similar to switch 258 can be grounded and provided on the opposite side of pushed member 256 so that when knob 218 is pulled in a direction opposited to direction 262, a button on this switch is engaged by the pusher member to detect the pulled motion. The pull motion of knob 218 can also be sensed in a continuous range similar to the push embodiments described above. In some embodiments, both push and pull motions of the knob 218 may be provided and sensed.

A spring member 264 is rigidly coupled to the pushing member 256 at one end and is rigidly coupled to a rotatable end member 266 at its other end. Spring member 264 is compressed when the knob 218 and pusher member 256 are moved in the direction of arrow 262. Spring member 264 thus provides a spring force that biases the knob 218 in the direction opposite to direction 262. If the knob 218 is not forced in direction 262, the spring bias moves the knob 218 opposite to direction 262 until the knob reaches its rest position. In those embodiments including a pull motion of the knob 218 in the direction opposite to direction 262, a spring member can be included on the opposite side of pusher member 256 to spring member 264, to bias the knob 218 in direction 262 after the user has pulled the knob. In yet other embodiments, no spring member 264 is provided, and the knob 218 remains at any pushed or pulled position until actively moved to a new position by the user.

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Spring member 264 also provides the transverse motion of knob 218 in the directions 228. The flexure of the spring element allows the knob to move in transverse degrees of freedom, while still being relatively torsionally stiff to allow forces to be transmitted effectively from an actuator to the knob 218 about axis A. In other embodiments, other types of couplings can be provided to allow a pivot or translational motion in the directions 228. For example, flexible disc servo couplings or one-piece flexible shaft disc couplings can be provided; such couplings are available from Renbrandt, Inc. of Boston, MA and Helical Products Company , Inc. of Santa Maria, CA. In other embodiments, bent space frames provided in a square-plate coupling or a rectangular coupling can be used. Furthermore, a different alternate flexible coupling embodiment is described in greater detail with respect to Figs. 4a-4c.

End member 266 is coupled to a rotatable shaft 268 of an actuator 270. The housing 272 of actuator 270 is rigidly coupled to grounded member 274, and the shaft 268 rotates with respect to the housing 272 and the member 274. Actuator 272 can be controlled to output force on rotating shaft 68 about axis A, thus driving the shaft and all components rigidly coupled to the shaft about axis A. The shaft 268 thus rotates end member 266, spring member 264, pusher member 256, shaft 250, and knob 218. The output force on knob 218 is felt by the user as force feedback. Actuator 270 can be any of a variety of different types of actuators, including a DC motor, voice coil, pneumatic or hydraulic actuator, magnetic particle brake, etc. A sensor 276 has a shaft rigidly coupled to the rotating shaft 268 of the actuator 270 and thus detects the rotation of the shaft 268 and the knob 218 about axis A. Sensor 276 is preferably a digital optical encoder but can alternatively be a different type of sensor, such as an analog potentiometer, a photodiode sensor, a Hall effect sensor, etc.

The force feedback output on knob 218 can include a variety of different force sensations. The force feedback can be integrally implemented with the control functions performed by the knob. A basic force sensation is force detents that are output at particular rotational positions of the knob to inform the user how much the knob has rotated and/or to designate a particular position of the knob. The force detents can be simple jolts or bump forces to indicate the detent's position, or the detents can include forces that attract the knob to the particular rotational detent position and resist movement of the knob away from that position. The position can correspond to a particular radio station frequency or other station (e.g., television station frequency), thus making selection easier for the user. Such detents can be provided for additional functions, such as volume control for sound speakers, fast forward or rewind of a video cassette recorder or computer-displayed movie (such as a DVD movie), scrolling a displayed document or web page, etc. Force feedback "snap-to" detents can also be provided, for example, for the favorite station frequencies preprogrammed by the user, where a small force biases the knob to the detent position when it is just outside the position.

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Also, the magnitude of the force detents can differ based on the value being controlled. For example, a radio frequency having a higher value might be associated with a stronger force detent, while a lower radio frequency might be associated with a weaker force detent when it is displayed, thus informing the user generally of the radio station being displayed without requiring the user to look at the display 214 (which is particularly useful when operating the device 210 while performing another task, such as driving a vehicle). In some embodiments, the user can also change the magnitude of detents associated with particular values, such as radio stations, to preferred values so as to "mark" favorite settings. Programmability of the location of the detents in the rotary degree of freedom is also convenient since preferred radio frequencies are most likely spaced at irregular intervals in the radio frequency range, and the ability to program the detents at any location in the range allows the user to set detents to those preferred stations. In addition, the knob can be moved by the actuator 270 to select the nearest preprogrammed station or preferred setting. Also, different sets of detent force profiles can be stored in a memory device on the device 230 and a particular set can be provided on the knob 218 by a microprocessor or other controller in the device 230.

Another type of force sensation that can be output on knob 218 is a spring force. The spring force can provide resistance to rotational movement of the knob in either direction to simulate a physical spring on the knob. This can be used, for example, to "snap back" the knob to its rest or center position after the user lets go of the knob, e.g. once the knob is rotated past a particular position, a function is selected, and the user releases the knob to let the knob move back to its original position. A damping force sensation can also be provided on knob 218 to slow down the rotation of the knob, allowing more accurate control by the user. Furthermore, any of these force sensations can be combined together for a single knob 218 to provide multiple simultaneous force effects.

The spring return force provided in the rotary degree of freedom of the knob 218 can also be used to implement a rate control paradigm. "Rate control" is the control of a rate of a function, object, or setting based on the displacement of the knob 218 from a designated origin position. The further the knob is moved away from the origin position, the greater the rate of change of controlled input. For example, if a rate control knob 218 with a spring return force is used to control the radio frequency, then the further the knob is moved from the center origin position, the faster the radio frequency will change in the appropriate direction. The frequency stops changing when the knob is returned to the origin position. The spring force is provided so that the further the user moves the knob away from the origin position, the greater the force on the knob in the direction toward the origin position. This feels to the user as if he or she is inputting pressure or force against the spring rather than rotation or displacement, where the magnitude of pressure dictates the magnitude of the rate. However, the amount of rotation of the

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knob is actually measured and corresponds to the pressure the user is applying against the spring force. The displacement is thus used as an indication of input force.

This rate control paradigm differs from the standard knob control paradigm, which is known as "position control", i.e. where the input is directly correlated to the position of the knob in the rotary degree of freedom. For example, in the radio frequency example, if the user moves the knob to a particular position, the radio frequency is changed to a particular value corresponding to the rotary position of the knob. Force detents are more appropriate for such a paradigm. In contrast, in the rate control example, moving the knob to a particular position causes the radio frequency to continue changing at a rate designated by the position of the knob.

Since the spring force and detent forces are programmable and can be output as directed by a microprocessor or other controller, a single knob 218 can provide both rate control and position control over functions or graphical objects. For example, a mode selector, such as a button or the push/pull knob motion, can select whether rate control or position control is used. One example of a force feedback device providing both rate control (isometric input) and position control (isotonic input) is described in greater detail in U.S. Patent No. 5,825,308, incorporated herein by reference. Such rate control and position control can be provided in the rotary degree of freedom of the knob 218. Also, if knob 218 is provided with force feedback in the transverse degrees of freedom or in the push/pull linear degree of freedom, then the rate control and position control modes can be provided in those degrees of freedom.

Other force sensations that can be output on knob 218 include forces that simulate ends of travel for the knob 218 or inform the user that the end of travel has been reached. For example, as the user rotates the knob in one direction to adjust the radio frequency 222, the end of the radio frequency range is reached. There is no hard stop on the knob 218 at this position, but the actuator 270 can be controlled to output an obstruction force to prevent or hinder the user from rotating the knob further in that direction. Alternatively, a jolt force can be output that is stronger in magnitude than normal detents, which informs the user that the end of the frequency range has been reached. The user can then continue to rotate the knob in that direction, where the displayed frequency 222 wraps around to the beginning value in the range.

In another alternate embodiment, one or more of the transverse motions of knob 218 in directions 228 can be actuated. For example, a greater range of motion can be provided for each transverse direction of the knob than typically allowed by a hat switch, and a linear or rotary actuator can be provided to output forces in the transverse degree of freedom, in one or both directions (toward the center position and away from the center position of the knob). For example, one or more magnetic actuators or solenoids can be used to provide forces in these transverse directions.

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Furthermore, in other embodiments, the pull and/or push motion of knob 218 along axis A can be actuated. For example, a jolt force can be output on the knob in the linear degree of freedom along axis A as the user pushes the knob. Also, the spring return force provided by spring member 264 can instead be output using an actuator controlled by a microprocessor.

It should be noted that the embodiment of Figs. 12a and 12b is not the only embodiment of the present invention. For example, some embodiments may only include the transverse motion of knob 18 and not the push and/or pull functionality nor the force feedback functionality. Other embodiments may only include the push and/or pull functions. Yet other embodiments may only include force feedback with transverse knob motion, or force feedback with push and/or pull functions.

FIGURE 13a is a perspective view of an alternate embodiment 280 of the control knob 218 of the present invention. In embodiment 280, knob 218 is coupled to shaft 250, which is rigidly coupled to a flex member 282. Flex member 282 includes a base plate 284 and a plurality of bent portions 286 extending from the base plate 284. For example, as shown in FIGURE 13b, the flex member 282 can be formed by cutting out the circular base plate 284 and the portions 286 from a unitary piece 285 of material, such as spring steel or stainless steel. The unitary piece is preferably provided as a thin sheet. Holes 288 or other apertures can be placed near the ends of the portions 286. Referring back to Fig. 13a, the portions 286 are then bent such that the holes 288 substantially align with the other holes 288, where the holes 288 are aligned with axis B that extends approximately perpendicular to the surface of the base plate 284. The base plate 284 is rigidly coupled to the rotating shaft of the actuator 270.

FIGURE 13c is a side elevational view of the embodiment 280 of Fig. 13a. In the described embodiment, knob 218 is coupled to shaft 250, which extends through a switch 290 and is coupled to the bent portions 286 of the flex member 282. The switch 290 is preferably similar to the switch 252 described above with reference to Figs. 12a and 12b. For example, a microswitch can be provided on the inside surface of the housing of switch 290 for each transverse direction of knob 218 that is to be sensed. The base plate 284 of the flex member 282 is rigidly coupled to shaft 292 of actuator 270. The shaft 292 is rigidly coupled to a shaft (not shown) of sensor 276, which has a grounded housing that is coupled to the grounded housing of actuator 270.

Alternatively, a plurality of sensors can be positioned external to the flex member 282 instead of using switch 290. For example, switches 294 can be positioned on two or more sides around the flex member 282, depending on how many directions are to be sensed. Switches 294 can be contact switches that each detect when the portions 286 move to engage the contact switch, thus indicating movement of knob 218 in a particular transverse direction. Alternatively, members can be positioned on shaft 250 which extend to the sides of the shaft and which engage

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electrical contacts or other sensors. In other embodiments, other switches or sensors can be used, as described above in the embodiment of Fig. 12a. A spring (not shown) can also be coupled to the shaft 250, flex member 282, or knob 218 to provide linear motion along the axis B and allow the knob 218 to be pushed and/or pulled by the user, as described in the embodiment of Fig. 12a. Some types of flexible couplings that allow transverse motion of the knob 218 may also allow linear motion along axis B, such as flexible disc servo couplings, in which case such as spring may not be needed.

In operation, the transverse motion of knob 218 in embodiment 280 operates as follows. The knob 218 is moved by the user approximately in a transverse direction 228, which causes the shaft 250 to move with the knob by pivoting approximately about the end of the shaft 250 where it is coupled to the portions 286. Shaft 250 is allowed such movement due to the flexibility in portions 286. In some embodiments, the knob 218 is also allowed to translate in a transverse direction 228 as well as or in addition to pivoting approximately in directions 228. When the knob 218 is rotated about axis B (by the user or the actuator), the shaft 250 rotates about its lengthwise axis, causing the flex member 282 to rotate about axis B. Since the portions 286 are stiff in the rotational direction about axis B, torque output on the shaft 250 and on the flex member 282 is transmitted accurately from actuator 270 to knob 218 and from knob 18 to sensor 276. Thus, the rotation on flex member 292 causes the shaft 92 to rotate, which is sensed by sensor 276. The rotational force about axis B output by actuator 70 is similarly transmitted from shaft 292, through flex member 282, to shaft 250 and knob 218.

FIGURE 14 is a perspective view of an exemplary embodiment for the slider control 232 as shown in Fig. 10. Slider control 232 includes slider knob 234 which may move in a linear degree of freedom as indicated by arrow 236. In the described embodiment, a transmission member 300 is rigidly coupled to the knob 234 and extends through a slit or opening 302 in the front panel 212 or other grounded member. Transmission member 300 can be coupled to an actuator, such as linear voice coil actuator 304.

The member 300 can move in and out of a housing 301 of actuator 304 as indicated by arrow 303. The housing 301 preferably includes a central core 307 and a number of elongated magnets 309. An armature 305 includes a hollow, cylindrical member having an inner surface which slidingly engages the core 307. Wrapped around the armature 305 are coils 310 that are electrically coupled to actuator and/or sensor interfaces. The armature 305 is coupled to the transmission member 300 so that the armature 305 and member 300 can move in a linear fashion as indicated at arrow 303. Other voice coil configurations can also be used, such as differently shaped cores, different coil layouts, etc. Voice coil actuator 304 can serve both as a sensor and an actuator. Alternatively, the voice coil can be used only as an actuator, and a separate sensor 306 can be used. Separate sensor 306 can be a linear sensor that senses the motion or position of an extension 312 that is coupled to the transmission member 300 and moves linearly when the

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transmission member moves. Voice coil actuators such as actuator 304 are described in greater detail in U.S. Patent No. 5,805,140, the disclosure of which is incorporated herein by reference. In particular, the operation of the voice coils as actuators and/or sensors is described therein.

Other types of actuators 304 and transmissions can also be used in slider control 232. For example, a capstan drive and cable transmission can provide linear forces on the knob 234. Other types of actuators suitable for use with the slider include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer, etc. Passive actuators may also be used, such as magnetic particle brakes, friction brakes, fluid controlled passive actuators, or other actuators which generate a damping resistance or friction in a degree of motion.

Slider knob 234 can also include a button 238 which is used to provide input to the device 210. In yet other embodiments, the slider knob 234 can be pushed and/or pulled in a linear degree of freedom approximately perpendicularly to the surface of front panel 212. In such an embodiment, a moveable contact switch can be provided between the knob 234 and the transmission member 300. A spring member can also be provided similarly to the embodiment of Figs. 12a-12b and 13a-13c to bias the knob 234 to a neutral rest position.

The force sensations and modes described above for the rotary knob in Figs. 12a-12b and 13a-13c may also be used for the slider control 232 in a linear degree of freedom. For example, force detents can be applied in a position control paradigm as the knob 234 is moved in its linear degree of freedom. In a rate control paradigm, a spring return force can bias the knob 234 toward a center origin position, for example the center of the range of motion of the knob. The further the user moves the knob from the origin position, the greater the spring force opposing that motion and the greater the rate of the controlled value changes (increases or decreases). Other force effects include damping forces, texture forces, jolts, obstruction forces, assistive forces, periodic forces such as vibration forces, and end-of-travel forces.

FIGURES 15a and 15b are diagrammatic illustrations illustrating detent force profiles suitable for use with the knobs of device 210. Detent force profiles can be implemented by a microprocessor or other controller based on instructions stored in a computer readable medium, such as a memory circuit, magnetic disk, optical disk, etc. In Fig. 15a, a detent force profile is shown. The vertical axis F represents the magnitude of force output, where a positive F value indicates force in one direction, and a negative F value indicates force in the opposite direction. The horizontal axis d represents the distance or position of the moved user object (knob) in a degree of freedom, where the origin position O indicates the position of the detent, a positive d is a position past the origin of the detent in one direction, and a negative d is a position past the origin of the detent in the opposite direction. The curve 324 represents the force output for a single detent over a position range for the detent. Thus, for example, if the user moves the knob

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clockwise toward the detent origin O1, the motion may be from the left toward the origin O1 on the axis d. A force toward the origin is output at position P1 at a magnitude -M to assist the user in moving the knob clockwise toward the origin. As the user continues to move the knob clockwise toward the origin O1, the assisting force is decreased in magnitude until no force is output when the knob is positioned at the origin position. If the user moves the knob counterclockwise from the origin position O1 (from right to left), the force will resist such motion in an increasing manner until the knob has been moved to position P1, after which the force magnitude drops to zero. Similarly, on the positive side of the d axis, if the user rotates the knob clockwise away from the detent origin position O1 (corresponding to movement from left to right), an increasing magnitude of force is output until the knob reaches the position P2, at which point the force magnitude drops from its maximum at M to zero. If the user moves the knob counterclockwise from position P2 toward the origin O1, the user initially feels a large magnitude force assisting that movement, after which the assisting force gradually decreases until it is zero at the origin O1. Preferably, point P1 is at an equal distance from origin O1 as point P2.

Additional detents may be positioned in the degree of freedom of the knob in successive positions, represented along axis d. For example, curve 326 represents another detent that is encountered shortly after leaving the previous detent curve 324 when turning the knob in a particular direction.

A problem occurring with closely spaced detents is that often the user moves the knob from a first detent to a second detent but unintentionally moves the knob past the second detent due to the assistive detent forces of the second detent. This is because the force from the user required to move the knob past the resistive force of the first detent curve is combined with the assistive force of the second detent curve, causing the knob to unintentionally move past the second origin and past the endpoint of the second detent curve. Furthermore, the same problem occurs when the user moves the knob in the opposite direction, from the second detent to the first detent. The user must exert force to overcome the resistance at the last point of the second detent curve, which causes the knob to quickly move past the first point of the first detent curve, where the assistive force is added to the motion to cause the knob to unintentionally move past the last encountered point of the first detent.

Fig. 15b shows a detent force profile of the present invention in which the detent forces of two successive detents are partially overlapped due to the detents, and provide a hysteresis-like force effect. The two detent curves 328 and 330 are identical, thus allowing a single force command to create the multiple detents if desired. Endpoint 331 of curve 328 is positioned at position P1 and endpoint 332 of curve 328 is positioned at position P2, where P2 is about the same distance from origin O1 as P1. Similarly, endpoint 334 of curve 330 is positioned at position P3 and endpoint 333 of curve 330 is positioned at position P4, where P4 is about the

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same distance from origin O2 as P3. Detent curve 328 ends at endpoint 332 on the right side of origin O1 and within the range of forces of detent curve 330. Preferably, the end point 332 of curve 328 is positioned well after the endpoint 334 of curve 330, such that the point 332 has a position in the middle of the range between point 334 and the origin O2. The overlapped zone is between positions P3 and P2. In addition, the end point 332 of the first detent preferably does not extend past the origin O2 of the second detent into the positive side of the second detent. If another detent is positioned further on the d axis after curve 330, the end point 333 of curve 330 preferably is positioned well after the starting endpoint of the next detent curve and not past the origin of the next detent curve. Similar positioning can be provided for curves before curve 328 on axis d.

To solve the problem of unintentionally moving past a successive detent, the range of the second or successive detent is adjusted such that a lesser magnitude is preferably output at the beginning of the successive detent than would normally be output if the entire curve of the successive detent were used. Furthermore, the force detent curve used to output force is preferably different depending on the direction of the knob, similar to a hysteresis effect. As shown in FIGURE 15c, when moving the knob so the knob position changes from left to right, the force at the beginning of the range of detent curve 330 is at point 335 having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint 333 of the range of curve 330 (ignoring the signs or direction of the forces). Of course, in other embodiments point 335 can have a magnitude of other fractions of M, such as one-third or three-fourths of M. Additional curve 327 can be similarly positioned and provide a similar overlap with curve 330, and additional curves may be added before curve 328 and/or after curve 327.

As shown in FIGURE 15d, when moving the knob in the other direction so the knob position changes from right to left, the endpoints of the curve 330 reverse in magnitude with respect to the endpoints shown in Fig. 15c. In Fig. 15d, starting from origin O2, the force at the beginning of the range of detent curve 328 is at point 336 having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint 331 of curve 328 (other fractions of M can be provided for endpoint 336 in other embodiments). Any additional curves, such as curve 327, can be provided with a similar overlap. The force output on the knob thus changes depending on the direction of the knob. In a digital sensing system (e.g. using a digital encoder), the direction can be determined from a history of sensed values. For example, one or more sensed position values can be stored and compared to a current sensed position to determine the knob direction.

The use of a lesser magnitude at the beginning of the second detent reduces the tendency of the user to unintentionally skip past a second detent after moving the knob over a first detent closely spaced to the second detent. For example, when moving the knob left to right (e.g., clockwise) from position P1, a first detent (curve 328) ends at point 332 of curve 328, after

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which the force magnitude of point 335 on curve 330 begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point 334, i.e. the beginning point of the full curve 330. Thus, less force is assisting the user to move toward the origin O2 of curve 330 than if the force magnitude for beginning point 334 of the curve 330 were in effect. With less force assisting motion toward origin O2, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O2. Furthermore, the changing of endpoints of the detent curve, as dependent on direction, provides a hysteresis-like effect the reduces the unintentional skip in both directions. Thus, when moving the knob from right to left (e.g., counterclockwise) starting at origin O2, a first detent (curve 330) ends at point 334 of curve 330, after which a magnitude of point 336 on curve 328 begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point 334. Thus, less force is assisting the user to move toward the origin O1 of curve 328 than if the force magnitude for beginning point 332 of the curve 328 were in effect. With less force assisting motion toward origin O1, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O1.

The same overlapping and hysteresis feature can be provided for differently-shaped detents as well, such as curved detents of Figs. 16a-16e, detents having deadbands around the origin O, and/or other-shaped force profiles. In embodiments having detent endpoints that are spaced further apart, or which have very gradually-sloping curves, the overlap and hysteresis may not be needed since there may be enough space in the degree of freedom for the user to control the knob from unintentionally moving past the next detent.

FIGURE 16a is a graph illustration 337 of a periodic wave 339 that can be used to provide a variety of detent force sensations for use with the knob control device of the present invention. The periodic wave represents force exerted on the knob (axis F) vs. the position or displacement (axis d) of the knob, similar to the force detent profile shown in Figs. 15a and 15b. The wave 339 is a periodic function, such as a sine wave, triangle wave, square wave, etc. In Fig. 16a, a sine wave shape is shown. In the present invention, a portion of the wave may be used to provide detent and other force sensations for the knob 218 or 234. Various parameters of the sine wave are shown in Fig. 16a, including period and magnitude.

Curve 338 (solid line) represents a detent force effect that has been created based on the sine wave 339. Curve 338 has a width, which is the amount of the wave 339 along axis d used for the force detent. The location of the detent is the position in the degree of freedom at which the detent force is centered, i.e. the location of the origin position O of the detent. A deadband can be defined to be a distance from the origin O to a specified point, a region in which zero forces are output on the knob. Thus, the curve 338 shown in Fig. 16a shows a detent force starting at a magnitude M1 at location P1 and, when the knob is moved toward the origin O, the force increases to the maximum point M2 at location P2 and then decreases until point P3, where

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the deadband is reached (zero magnitude). Similarly, at point P4 on the other side of the origin O, the force increases from zero to a maximum magnitude M5 at location P5, after which the force drops a short distance to magnitude M6 at location P6. The force then drops to zero for increasing d, until another detent effect is encountered. The small decreases in force magnitude from the maximum magnitude at the end points of the curve 338 are useful in some detent embodiments to provide a less extreme assistive or resistive force to the user when entering or exiting the detent range, e.g., to gradually lead the user into the detent range before outputting the maximum force. This can provide a smoother-feeling and, in some cases, a more easily-selected detent (i.e., it can be easier to position the knob at the detent's origin).

The detent curve 338 can thus be defined using the parameters shown in Fig. 16a. For example, a force command protocol can provide a number of different commands that can cause the output of different force sensations to the user. The commands can each include a command identifier followed by one or more command parameters that define and characterize the desired force sensation. An example of a command defining a detent curve 338 is as follows:

DETENT (TYPE, PERIOD, MAGNITUDE, LOCATION, DEADBAND, FLAG, WIDTH, PHASE, OFFSET, LOCATION, INCREMENT, ARRAY POINTER)

The DETENT identifier indicates the type of force sensation. The TYPE parameter indicates a type of periodic wave from which to base the force detent curve, such as a sine wave, triangle wave, square wave, ramp, etc. The PERIOD and MAGNITUDE parameters define those characteristics of the periodic wave. The LOCATION parameter defines the location of the origin position for the detent in the degree of freedom of the knob. The DEADBAND parameter indicates the size of the deadband around the origin position. The FLAG parameter is a flag that indicates whether the detent is provided on the positive side, the negative side, or both sides around the location (origin position). The WIDTH parameter defines the amount of the wave 339 used for the detent curve, i.e. the extent of the wave used starting from the PHASE position. The PHASE parameter indicates the starting position of the detent curve 338 on the wave 339 (and is described in greater detail below). The OFFSET parameter indicates the amount of magnitude offset that curve 338 includes from the d axis, and is described in greater detail below. The INCREMENT parameter indicates the distance in the degree of freedom of the knob between successive detent locations. The optional LOCATION ARRAY POINTER parameter indicates a location in a separate array that has been previously programmed with the particular positions in the degree of freedom of the knob at which the detents are located and (optionally) the total number of detents; the array can be provided in memory, such as RAM, or other writable storage device. For example, the array can be preprogrammed with three detents, at locations of 45 degrees, 78 degrees, and 131 degrees in the rotation of the knob. The array can be accessed as necessary to retrieve these locations at which detent forces are to be output. This

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can be useful when the detent locations are not evenly or regularly spaced in the degree of freedom, and/or when a particular number of detents is desired to be output.

Furthermore, in other embodiments, a periodic wave can be additionally "shaped" to form a particular detent curve. For example, an "envelope" can be applied to a periodic wave to shape the wave in a particular way. One method of shaping a wave is to define a first magnitude and a settle width, which is the distance required for the wave to settle to a second, lesser magnitude from the first magnitude. This settle width thus provides a ramping shape to the upper and/or lower portions of the periodic wave about axis d. Although such shaping is performed in a spatial domain, it is similar to shaping a signal in the time domain. The shaping can be specified by parameters in a commands, such as a settled width parameter, magnitude parameters, etc.

The detent command can be sent by a supervisory microprocessor to a lower-level local microprocessor to decode and interpret the commands to control procedures provided in device 210 in firmware or other storage medium, as described with reference to Fig. 17 below. If a host computer and local microprocessor are used, the host computer can send the command to the local microprocessor, which parses/decodes and interprets the command and causes appropriate forces to be output. Commands and protocols for use in force feedback are described in greater detail in U.S. Patent 5,734,373, incorporated by reference herein. Such commands can also be retrieved from a storage device such as memory and then parsed and interpreted by a local microprocessor.

The ability to define a force detent (in the spatial domain) in terms of a periodic waveform can be useful in force feedback implementations in which periodic force effects in the time domain are also provided. For example, vibration force sensations can be provided by outputting a periodic sine wave or square wave for the magnitude of the force over time. If such time-based effects can be output on knob 218 or 234, then it is convenient to use the same periodic wave definitions and data for defining force vs. position profiles for detents as shown in Figs. 16a-16e.

FIGURE 16b is a graph illustration 340 showing particular parameters of the detent command described above which are applied to a periodic wave. Sine wave 342 has a magnitude and period as shown. A specified phase of the desired detent curve causes the detent curve to start at a position on wave 342 in accordance with the phase. For example, in Fig. 16b, a phase of 50 degrees is specified. This will cause the resulting detent curve to start at point P on the wave 342. A width parameter specifies the amount of the wave from the phase location to be used as the detent curve. Furthermore, an offset of -0.8 is indicated. This causes the resulting detent curve to be shifted down by 80% from the wave 342. Furthermore, a deadband is also specified (not shown in Fig. 16b.).

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FIGURE 16c is a graph 344 showing the resulting detent curve 346 obtained from the application of the parameters to the wave 342 described with reference to Fig. 16b. The portion of the wave 342 starting at the phase and positioned above the offset line in Fig. 16b is used in the detent curve 346. Furthermore, a deadband 348 has been added to the curve. The flag in the detent command has caused the positive side of the curve 346 to be mirrored on the negative side of the origin O. This detent curve 346 causes a detent force that is similar to the detent force described with reference to Fig. 16a, only smaller in magnitude and in position range over the degree of freedom of the knob.

FIGURE 16d is a graph 360 showing a periodic wave and parameters to be applied to the wave. Sine wave 362 is provided as described above, having a particular period and magnitude. An offset is specified for the resulting detent curve; in the example of Fig. 16d, the offset is 1, thus causing the detent curve to be shifted upward by its entire magnitude. A phase of 270 degrees is also indicated, so that the detent curve starts at the lowest magnitude of the wave 372 at point P. Furthermore, an increment is also specified as a parameter (not shown). FIGURE 16e is a graph 370 illustrating the detent curves 372 and 374 resulting from the wave 362 and parameters described with reference to Fig. 16d. The portion of the wave 362 past point P and ending at a point defined by a width parameter is provided both on the positive side and the negative side of origin O1 of graph 370 for curve 372 (the positive and negative sides are designated by the flag parameter). A second curve 374 is also shown, where the origin O2 of the second curve is positioned at a distance from the origin O1 as specified by the increment parameter. Additional curves similar to curves 372 and 374 are provided at further distances at same increment from each other. The detent curves 372 and 374 provide a much steeper, less gradual detent force over the detent range than the other detent forces shown in Figs. 16a and 16c. Furthermore, no actual deadband is specified, although the shape of each half of the curve 372 provides a small zone 376 where zero force is output, similar to a deadband.

FIGURE 17 is a block diagram illustrating an electromechanical system 400 for the device 210 of Fig. 10 suitable for use with the present invention. A force feedback system including many of the below components is described in detail in Patent number 5,734,373.

In one embodiment, device 210 includes an electronic portion having a local microprocessor 402, local clock 404, local memory 406, sensor interface 408, and actuator interface 410.

Local microprocessor 402 is considered local to device 210 and is preferably similar in type and function to microprocessor 90, described above. Microprocessor 402 can include one microprocessor chip, or multiple processors and/or co-processor chips, and can include digital signal processor (DSP) functionality. Also, "haptic accelerator" chips can be provided which

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are dedicated to calculating velocity, acceleration, and/or other force-related data. Alternatively, fixed digital logic and/or state machines can be used to provide similar functionality.

A local clock 404 can be coupled to the microprocessor 402 to provide timing data, for example, to compute forces to be output by actuator 270; or timing data for microprocessor 402 can be retrieved from the USB interface. Local memory 406, such as RAM and/or ROM, is preferably coupled to microprocessor 402 in interface device 210 to store instructions for microprocessor 402, temporary and other data, calibration parameters, adjustments to compensate for sensor variations, and/or the state of the device 210. Display 214 can be coupled to local microprocessor 402 in some embodiments. Alternatively, a different microprocessor or other controller can control output to the display 214.

Sensor interface 408 may optionally be included in device 210 to convert sensor signals to signals that can be interpreted by the microprocessor 402. Alternately, microprocessor 402 can perform these interface functions. Actuator interface 410 can be optionally connected between the actuator 270 and microprocessor 402 to convert signals from microprocessor 402 into signals appropriate to drive the actuators. Actuator interface 410 can include power amplifiers, switches, digital to analog controllers (DACs), and other components, as well known to those skilled in the art. In alternate embodiments, actuator interface 410 circuitry can be provided within microprocessor 402 or in the actuator 270. A power supply 412 can be coupled to actuator 270 and/or actuator interface 410 to provide electrical power. In a different embodiment, power can be supplied to the actuator 270 and any other components (as required) by an interface bus. Power can also be stored and regulated by device 210 and thus used when needed to drive actuator 270.

A mechanical portion is included in device 210, an example of which is shown above in Figs. 12a-12b and 13a-13c. The mechanical portion can include some or all of the components needed for rotational motion of knob 218, transverse motion of knob 218, the push and/or pull motion of knob 218, and force feedback in any or all of these degrees of freedom of the knob.

Mechanical portion 400 preferably includes sensors 414, actuator 270, and mechanism 416. Sensors 414 sense the position, motion, and/or other characteristics of knob 218 along one or more degrees of freedom and provide signals to microprocessor 402 including information representative of those characteristics. Typically, a sensor 414 is provided for each degree of freedom along which knob 218 can be moved, or, a single compound sensor can be used for multiple degrees of freedom. Sensors 414 can include sensor 276, switch 252, and switch 258 as shown in Figs. 12a-12b. For example, one switch 252 of Figs. 12a-12b or switch 290 of Fig. 13c can include a sensor switch for each transverse direction 228 that the knob 218 can be moved. Examples of sensors suitable for rotary sensor 276 of Figs. 12a-12b and 13a-13c include optical encoders, analog sensors such as potentiometers, Hall effect magnetic sensors, optical sensors

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such as a lateral effect photo diodes, tachometers, and accelerometers. Furthermore, both absolute and relative sensors may be used.

In those embodiments including force feedback, actuator 270 transmits forces to knob 218 in one or more directions in a rotary degree of freedom in response to signals output by microprocessor 402 or other electronic logic or device, i.e., it is "electronically-controlled." The actuator 270 produces electronically modulated forces which means that microprocessor 402 or other electronic device controls the application of the forces. Typically, an actuator 270 is provided for each knob 218 that includes force feedback functionality. In some embodiments, additional actuators can also be provided for the other degrees of freedom of knob 218, such as the transverse motion of the knob 18 and/or the push or pull motion of the knob. The actuators, such as actuator 270, can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), voice coil actuators, etc. Passive actuators can also be used, including magnetic particle brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. In some embodiments, all or some of sensors 414 and actuator 270 can be included together as a sensor/actuator pair transducer, as shown in Figs. 12a-12b for actuator 270 and sensor 276.

Mechanism 416 is used to translate motion of knob 218 to a form that can be read by sensors 414, and, in those embodiments including force feedback, to transmit forces from actuator 270 to knob 218. Examples of mechanism 416 are shown with respect to Figs. 12a-12b and 13a-13c. Other types of mechanisms can also be used, as disclosed in U.S. Patent Nos. 5,767,839, 5,721,566, 5,805,140, all incorporated by reference herein. Also, a drive mechanism such as a capstan drive mechanism can be used to provide mechanical advantage to the forces output by actuator 270, as described in patent no. 5,731,804, incorporated by reference herein. Alternatively, a belt drive system, gear system, or other mechanical amplification/transmission system can be used.

Other input devices 420 can be included in interface device 210 and send input signals to microprocessor 402. Such input devices can include buttons, such as buttons 216 on front panel 212 as shown in Fig. 10, used to supplement the input from the knob to the device 210. Also, dials, switches, voice recognition hardware (e.g. a microphone, with software implemented by microprocessor 402), or other input mechanisms can be used. can also be included to send a signal (or cease sending a signal) to microprocessor 402 or to the actuator 270 or actuator interface 410, indicating that the user is not gripping the knob 218, at which point all output forces are ceased for safety purposes. A safety or "deadman" switch 422 can optionally be included for the knob 218 in those implementations providing force feedback on the knob. Such a safety switch can be implemented similarly to safety switch 115 described above with

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reference to Fig. 4. Safety switches are also described in patent no. 5,691,898. incorporated by reference herein.

Other microprocessor 424 can be included in some embodiments to communicate with local microprocessor 402. Microprocessors 402 and 424 are preferably coupled together by a bi-directional bus 426. Additional electronic components may also be included for communicating via standard protocols on bus 426. These components can be included in device 210 or another connected device. Bus 426 can be any of a variety of different communication busses. For example, a bi-directional serial or parallel bus, a wireless link, a network architecture (such as Canbus), or a uni-directional bus can be provided between microprocessors 424 and 402.

Other microprocessor 424 can be a separate microprocessor in a different device or system that coordinates operations or functions with the device 210. For example, other microprocessor 424 can be provided in a separate control subsystem in a vehicle or house, where the other microprocessor controls the temperature system in the car or house, or the position of mechanical components (car mirrors, seats, garage door, etc.), or a central display device that displays information from various systems. Or, the other microprocessor 424 can be a centralized controller for many systems including device 210. The two microprocessors 402 and 424 can exchange information as needed to facilitate control of various systems, output event notifications to the user, etc. For example, if other microprocessor 424 has determined that the vehicle is overheating, the other microprocessor 424 can communicate this information to the local microprocessor 202, which then can output a particular indicator on display 214 to warn the user. Or, if the knob 218 is allowed different modes of control, the other microprocessor 424 can control a different mode. Thus, if the knob 218 is able to control both audio stereo output as well as perform temperature control, the local microprocessor 402 can handle audio functions but can pass all knob sensor data to other microprocessor 424 to control temperature system adjustments when the device 210 is in temperature control mode.

In other embodiments, other microprocessor 424 can be a microprocessor in a host computer, for example, that commands the local microprocessor 402 to output force sensations by sending host commands to the local microprocessor. The host computer can be a personal computer, workstation, video game console, or other computing or display device as described in previous embodiments. The host computer can implement a host application program with which a user interacts using knob 218 and/or other controls and peripherals. The host application program can be responsive to signals from knob 218 such as the transverse motion of the knob, the push or pull motion, and the rotation of the knob (e.g., the knob 218 can be provided on a game controller or interface device such as a game pad, joystick, steering wheel, or mouse that is connected to the host computer). In force feedback embodiments, the host application program can output force feedback commands to the local microprocessor 402 and to the knob 218. In a host computer embodiment or other similar embodiment, microprocessor 402

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can be provided with software instructions to wait for commands or requests from the host computer, parse/decode the command or request, and handle/control input and output signals according to the command or request.

For example, in one force feedback embodiment, host microprocessor 424 can provide low-level force commands over bus 426, which microprocessor 402 directly transmits to the actuators. In a different force feedback local control embodiment, host microprocessor 424 provides high level supervisory commands to microprocessor 402 over bus 426, and microprocessor 402 manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer, similar to the embodiments for wheel 16 described above.

In an alternate embodiment, no local microprocessor 402 is included in interface device 210, and a remote microprocessor, such as microprocessor 424, controls and processes all signals to and from the components of interface device 210. Or, hardwired digital logic can perform any input/output functions to the knob 218.

While this invention has been described in terms of several preferred embodiments, it is contemplated that alterations, permutations and equivalents thereof will become apparent to those skilled in the art upon a reading of the specification and study of the drawings. For example, many types of actuators, sensors, and mechanisms can be used to sense and apply forces on the wheel or knob. In addition, the wheel or knob itself can be implemented in a variety of ways, as a dial, cylinder, knob, sphere, or other shape. Also, a great variety and types of force sensations can be output on wheel 16. It should also be noted that the embodiments described above can be combined in various ways in a particular implementation. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. It is therefore intended that the following appended claims include all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.

What is claimed is:

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CLAIMS

1. An interface device for interfacing a user's input with a host computer and providing force feedback to said user, said interface device comprising:

a user manipulandum contacted and manipulated by a user and moveable in a planar workspace with respect to a ground surface;

a manipulandum sensor coupled to said user manipulandum for detecting a position of said user manipulandum in said planar workspace and operative to send a position signal to said host computer indicating a position of said user manipulandum in said workspace;

a rotatable wheel coupled to said user manipulandum and rotatable about a wheel axis;

a wheel sensor coupled to said wheel and providing a wheel signal to said host computer indicating a rotary position of said wheel;

a wheel actuator coupled to said rotatable wheel and operative to apply a computer-modulated force to said rotatable wheel about said wheel axis, wherein said force is modulated as a function of time or wheel position about said wheel axis.

2. An interface device as recited in claim 1 wherein said user manipulandum includes a mouse object.

3. An interface device as recited in claim 2 wherein said manipulandum sensor includes a ball and roller assembly.

4. An interface device as recited in claim 2 further comprising an actuator for applying a force to said user manipulandum in said workspace.

5. An interface device as recited in claim 2 wherein said rotary wheel rotates about an axis parallel to said planar workspace.

6. An interface device as recited in claim 2 wherein said wheel actuator is coupled to said wheel by a belt drive mechanism.

7. An interface device as recited in claim 2 wherein said wheel actuator is directly coupled to said wheel.

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8. An interface device as recited in claim 2 wherein said wheel can be depressed into a housing of said user manipulandum.

9. An interface device as recited in claim 2 wherein said wheel is coupled to a first shaft that is coupled to and rotatable about a second shaft, said second shaft being coupled to said wheel actuator.

10. An interface device as recited in claim 1 further comprising a local microprocessor, separate from host computer, coupled to said actuator and controlling said actuator to apply said computer-modulated force on said wheel.

11. An interface device as recited in claim 1 wherein said host computer is running a graphical environment and wherein said force applied to said wheel corresponds with an event or interaction displayed in said graphical environment.

12. An interface device as recited in claim 1 wherein said wheel actuator outputs a set of isotonic forces when said interface device is in an isotonic mode, and wherein said wheel actuator outputs a set of isometric forces when said interface device is in an isometric mode.

13. A handheld force feedback remote control device for providing input to an electronic device located remotely from said remote control device, the remote control device comprising:

a wheel rotatably coupled to a housing of said remote control device and rotatable about an axis, said wheel being manipulated by a user;

an actuator coupled to said wheel for outputting a computer-modulated force detent on said wheel, said force detent felt by said user, wherein said force detent is provided at a predetermined rotational position of said wheel; and

a sensor that senses rotation of said wheel and provides a wheel signal to said electronic device indicating a rotary position of said wheel.

14. A force feedback wheel device as recited in claim 13 wherein said force detent includes an attractive force for biasing said wheel to said predetermined rotational position

15. A force feedback wheel device as recited in claim 13 wherein said remote control device sends signals to said electronic device using wireless transmission of information using an electromagnetic beam.

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16. A force feedback wheel device as recited in claim 13 wherein said electronic device includes a video game console and wherein said remote control device includes a game controller for inputting signals to said video game console.

17. A force feedback wheel device as recited in claim 13 wherein additional forces can be applied to said wheel, said additional forces including at least one of a damping force sensation, an inertial force sensation, a friction force sensation, a spring force sensation, a force detent sensation, an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

18. A force feedback wheel device for providing input to an electronic radio, the wheel device comprising:

a wheel rotatably coupled to a housing of said electronic radio and rotatable about an axis, said wheel being manipulated by a user;

an actuator coupled to said wheel for outputting a computer-modulated force detent on said wheel, said force detent felt by said user, wherein said force detent is provided at a predetermined user-preferred rotational position of said wheel; and

a sensor that senses rotation of said wheel and provides a wheel signal to said electronic device indicating a rotary position of said wheel;

19. A force feedback wheel device as recited in claim 18 wherein said force detent includes an attractive force for biasing said wheel to said predetermined rotational position

20. A force feedback wheel device as recited in claim 18 wherein said predetermined user-preferred positions are positions of preferred radio station frequencies in a radio frequency range.

21. A force feedback wheel device as recited in claim 18 wherein additional forces can be applied to said wheel, said additional forces including at least one of a damping force sensation, a spring force sensation, an inertial force sensation, a friction force sensation, a force detent sensation, an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

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22. A method for providing a force feedback mouse wheel on a mouse interface device, said mouse interface device coupled to a host computer, the method comprising:

sensing a position of a mouse of said mouse interface device in a planar workspace and sending an indication of said position to a host computer;

sensing a rotation of said mouse wheel about an axis of rotation and sending a wheel signal to said host computer indicating a current position of said wheel about said axis; and

applying a force to said mouse wheel about said axis using a wheel actuator coupled to said mouse wheel, wherein said force is coordinated with an event occurring in said graphical environment.

23. A method as recited in claim 22 wherein said sensing a rotation of said mouse wheel includes sensing an absolute position of said mouse wheel about said axis.

24. A method as recited in claim 22 wherein said applying a force to said mouse wheel is commanded by a local microprocessor included in said mouse interface device and separate from said host computer.

25. A method as recited in claim 22 wherein said event is a scrolling of a displayed document as controlled by said sensed rotation of said mouse wheel and said wheel signal.

26. A method as recited in claim 22 wherein said event is an interaction of a cursor with a graphical object implemented by said host computer, said cursor having motion influenced by said rotation of said wheel.

27. A method as recited in claim 26 wherein said interaction is a collision of said cursor with said graphical object.

28. A method as recited in claim 22 wherein said force is one of a damping force sensation, an inertial force sensation, and a friction force sensation.

29. A method as recited in claim 22 wherein said force is a force detent sensation.

30. A method as recited in claim 22 wherein said force is one of an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

31. A method as recited in claim 22 further comprising applying a force to said mouse object in said planar workspace using an actuator different from said wheel actuator.

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32. A knob controller device comprising:

a knob coupled to a grounded surface, said knob rotatable in a rotary degree of freedom about an axis extending through said knob, said knob also moveable in a transverse direction approximately perpendicular to said axis;

a rotational sensor that detects a position of said knob in said rotary degree of freedom;

a transverse sensor operative to detect a position of said knob in said transverse direction; and

an actuator coupled to said knob and operative to output a force in said rotary degree of freedom about said axis.

33. A knob controller device as recited in claim 32 wherein said knob is also moveable in a linear degree of freedom approximately parallel to said axis, and further comprising a linear sensor operative to detect a position of said knob in said linear degree of freedom.

34. A knob controller device as recited in claim 33 wherein said knob can be pushed or pulled by a user, said pushing or pulling motion being detected by said linear sensor.

35. A knob controller device as recited in claim 32 wherein said knob is moveable in a plurality of transverse directions, and wherein said transverse sensor is operative to detect when said knob is moved in any of said transverse directions.

36. A knob controller device as recited in claim 32 wherein said transverse sensor includes a hat switch having a plurality of individual switches, each of said individual switches detecting movement of said knob in a particular transverse direction.

37. A knob controller device as recited in claim 36 wherein said knob is moveable in four transverse directions spaced approximately orthogonal to each other, and wherein said hat switch includes four individual switches.

38. A knob controller device as recited in claim 32 further comprising a microprocessor coupled to said rotational sensor and to said transverse sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor signals.

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39. A knob controller device as recited in claim 38 wherein said device is an audio device.

40. A knob controller device as recited in claim 32 further comprising a microprocessor coupled to said rotational sensor and to said transverse sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor signals, said microprocessor sending force feedback signals to said actuator to control forces output by said actuator.

41. A knob controller device as recited in claim 32 further comprising a display, wherein an image on said display is changed in response to manipulation of said knob in said transverse direction.

42. A knob controller device as recited in claim 32 wherein a flexible member is coupled between said knob and said actuator to allow said movement in said transverse direction.

43. A knob controller device as recited in claim 42 wherein said flexible member is a spring member.

43. A knob controller device as recited in claim 42 wherein said flexible member includes a base plate and a plurality of bent flexible portions coupled to said base plate.

44. A knob controller device comprising:

a knob coupled to a grounded surface, said knob rotatable in a rotary degree of freedom about an axis extending through said knob, said knob also moveable in a linear degree of freedom approximately parallel to said axis;

a rotational sensor that detects a position of said knob in said rotary degree of freedom;

a linear sensor that detects a position of said knob in said linear degree of freedom; and

an actuator coupled to said knob and operative to output a force in said rotary degree of freedom about said axis.

45. A knob controller device as recited in claim 44 further comprising a microprocessor coupled to said rotational sensor and to said linear sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor

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signals, said microprocessor sending force feedback signals to said actuator to control forces output by said actuator.

46. A knob controller device as recited in claim 44 wherein said knob can be pushed by a user, said pushing motion being detected by said linear sensor.

47. A knob controller device as recited in claim 44 wherein said knob can be pulled by a user, said pulling motion being detected by said linear sensor.

48. A knob controller device as recited in claim 44 wherein said knob can be pushed or pulled by a user, said pushing motion and said pulling motion being detected by said linear sensor.

49. A knob controller device as recited in claim 44 said knob is also moveable in a plurality of transverse directions approximately perpendicular to said axis, and further comprising a transverse sensor operative to detect movement of said knob in any of said transverse directions.

50. A knob controller device as recited in claim 44 further comprising a spring member for biasing said knob to a center position in said linear degree of freedom.

51. A knob controller device as recited in claim 44 wherein said linear sensor detects a position of said knob within a detectable continuous range of motion of said knob, and wherein said linear sensor outputs a sensor signal indicative of said position.

52. An interface control device including force feedback and providing rate control and position control modes, the interface control device comprising:

a knob grasped by a user and movable in a degree of freedom;

an actuator coupled to said knob and providing forces on said knob in said degree of freedom;

a sensor that detects a position of said knob in said degree of freedom and outputs a sensor signal including information representing said position;

a microprocessor coupled to said actuator and to said sensor, said microprocessor controlling said forces provided by said actuator and receiving said sensor signal from said sensor, wherein said microprocessor commands either a position control mode or a rate control mode for said knob, wherein said position control mode controls a value based on a position of said knob in said degree of freedom, and wherein said rate control mode controls a rate of

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change of said value based on a position of said knob in said degree of freedom, wherein said rate control mode provides a force on said knob using said actuator, said force being applied in a direction opposing a movement of said knob away from an origin position.

53. An interface control device as recited in claim 52 wherein said degree of freedom is a rotary degree of freedom.

54. An interface control device as recited in claim 52 wherein said degree of freedom is a linear degree of freedom.

55. An interface control device as recited in claim 52 wherein said force opposing said movement is a spring force.

56. An interface control device as recited in claim 52 wherein said microprocessor controls said actuator to output at least one force detent during movement of said knob in said position control mode.

57. An interface control device as recited in claim 52 wherein said rate control mode is used to control the value of a volume, bass, treble, or balance function of said device.

58. An interface control device as recited in claim 52 wherein said position control mode is used to control the value of a volume, bass, treble, or balance function of said device.

59. An interface control device as recited in claim 52 wherein said rate control mode is used to control a position of a physical component in a vehicle.

60. A method for providing detent forces for a force feedback control, the method comprising:

outputting a first force for a first detent on a user manipulatable object contacted by a user and moveable in a degree of freedom, said first force being output when said user manipulatable object is moved within a range of said first detent, said first force being output by a electronically-controlled actuator, wherein said first force assists movement of said user manipulatable object toward an origin position of said first detent and wherein said first force resists movement of said user manipulatable object away from said origin position of said first detent; and

outputting a second force for a second detent on said user manipulatable object when said user manipulatable object is moved within a range of said second detent, said second force being

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output by said actuator and said second detent having an origin position different from said origin position of said first detent, wherein said second force assists movement of said user manipulatable object toward an origin position of said second detent and wherein said second force resists movement of said user manipulatable object away from said origin position of said second detent, wherein a portion of said range of said first detent overlaps a portion of said range of said second detent.

61. A method as recited in claim 60 wherein said first force for said first detent has a magnitude that increases the further that said user manipulatable object is positioned from said origin of said first detent, and wherein said second force for said second detent has a magnitude that increases the further that said user manipulatable object is positioned from said origin of said second detent.

62. A method as recited in claim 60 wherein a deadband is provided around said origin of said first detent and around said origin of said second detent, wherein a magnitude of said first force and said second force is zero when said user manipulatable object is positioned within said deadband.

63. A method as recited in claim 60 wherein when said user manipulatable object is moved in a particular direction from said first detent to said second detent, said first detent range has an endpoint positioned after a beginning point of said second detent range such that a force at said beginning point of said second detent range has less magnitude than a force at an endpoint of said second detent range.

64. A method as recited in claim 63 wherein when said user manipulatable object is moved in a direction opposite to said particular direction from said second detent to said first detent, a force at a first-encountered point of said first detent range has less magnitude than a force at a last-encountered point of said first detent range.

65. A method as recited in claim 63 wherein said first detent range does not overlap past said origin of said second detent.

66. A method as recited in claim 60 wherein said user manipulatable object is a knob and said degree of freedom is a rotary degree of freedom.

67. A method for providing detent forces for a force feedback control, the method comprising:

defining a periodic wave;

using at least a portion of said periodic wave to define a detent force curve, said detent force curve defining a force to be output on a user manipulatable object based on a position of

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said user manipulatable object in a degree of freedom, said user manipulatable object being contacted and moveable by a user; and

using said detent force curve to command said force on said user manipulatable object, said force being output by a electronically-controlled actuator.

68. A method as recited in claim 67 wherein said defining a periodic wave includes specifying a type, a period and a magnitude for said periodic wave.

69. A method as recited in claim 67 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying a portion of said periodic wave to define a width of said detent force curve.

70. A method as recited in claim 69 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying a phase and an offset to be applied to said periodic wave to define said detent force curve.

71. A method as recited in claim 67 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying an increment distance, wherein successive detent force curves in said degree of freedom are spaced apart by said increment distance.

72. A method as recited in claim 67 wherein said user manipulatable object is a knob moveable in a rotary degree of freedom.

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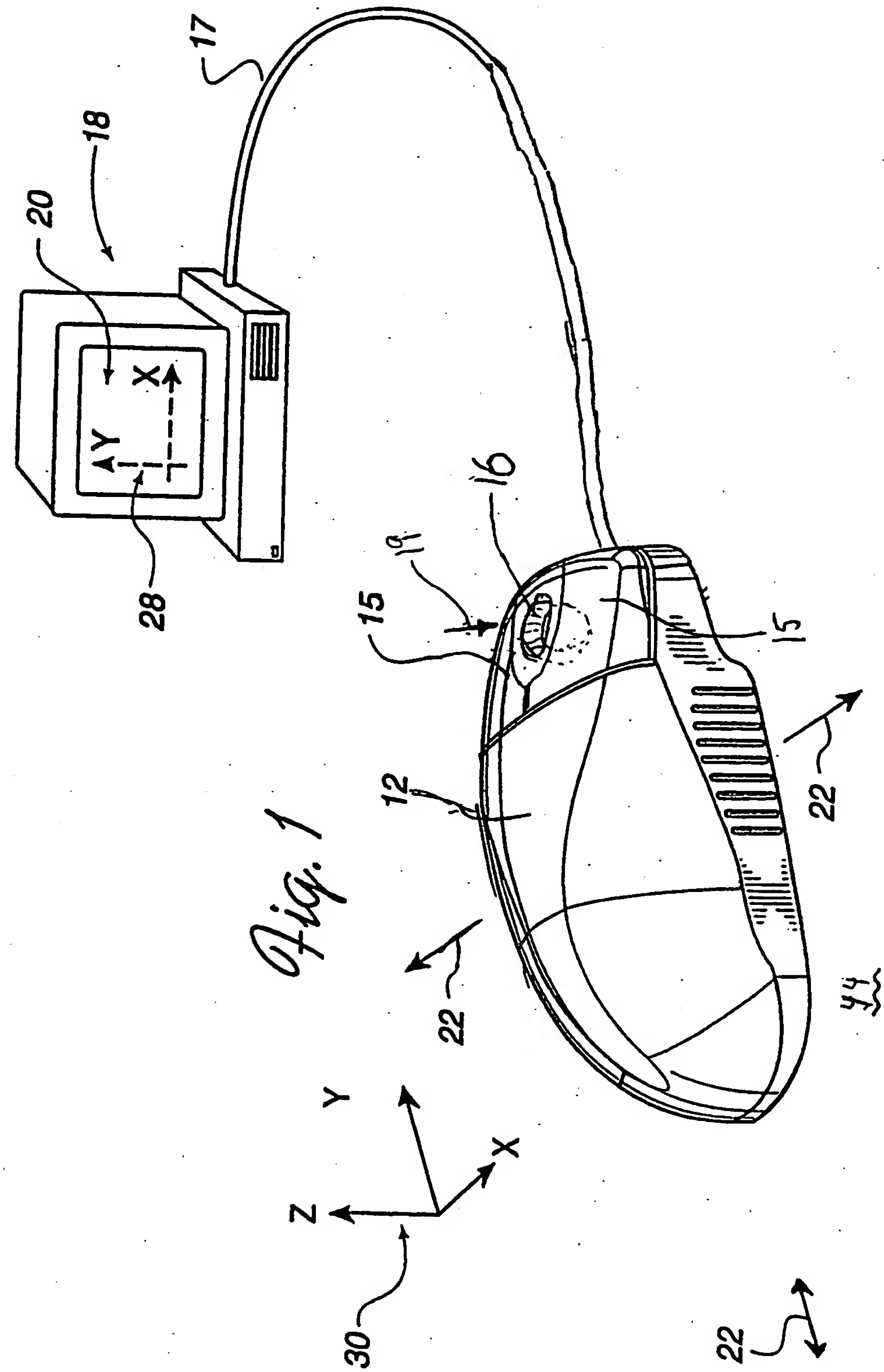

Fig. 1

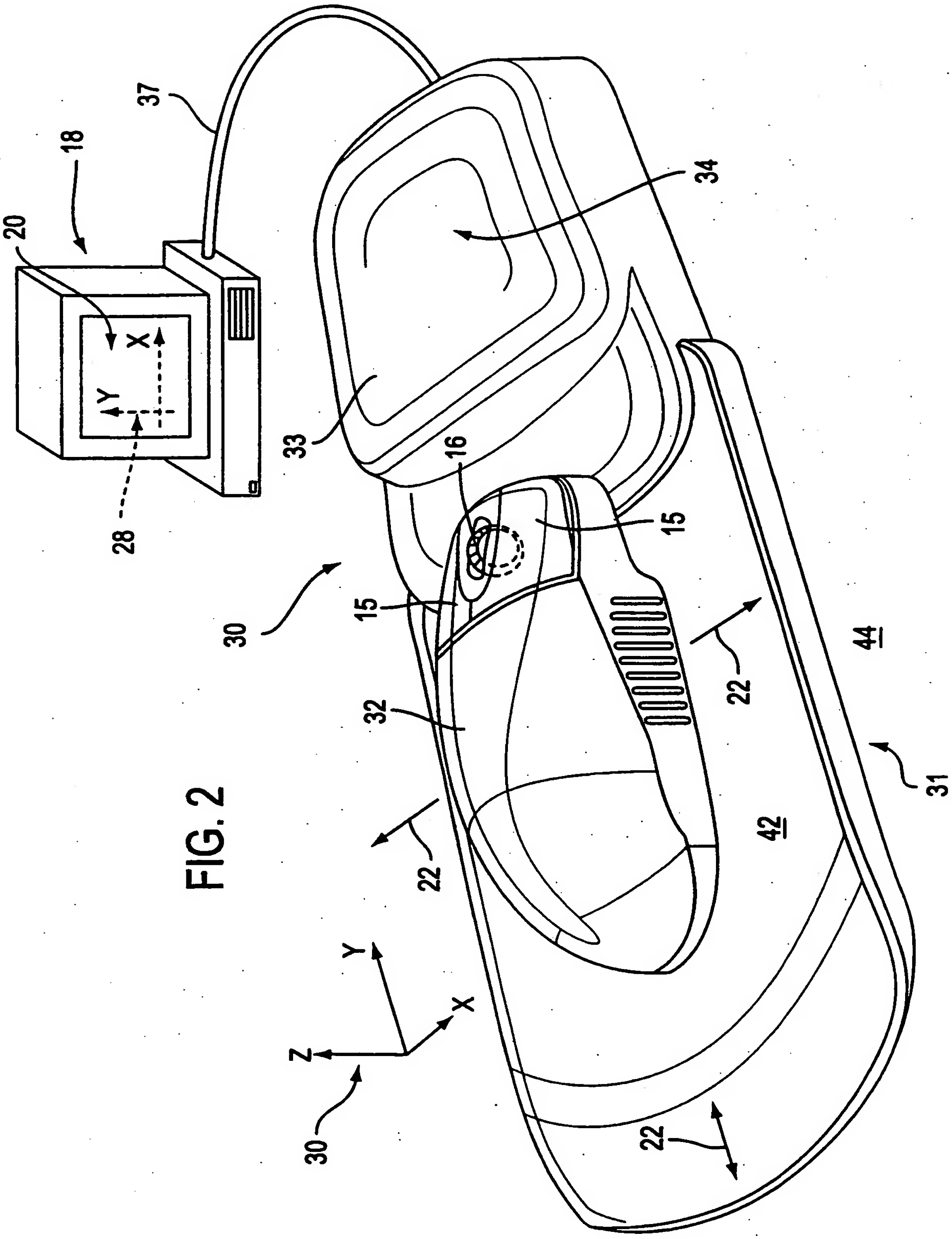

FIG. 2

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FIG. 3A

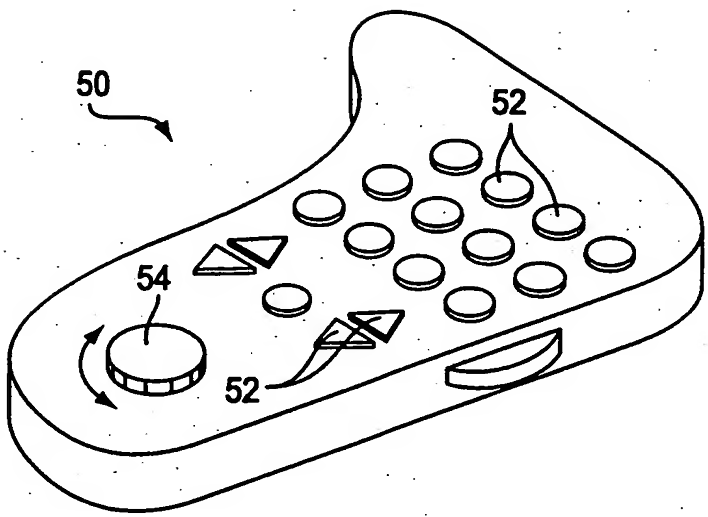
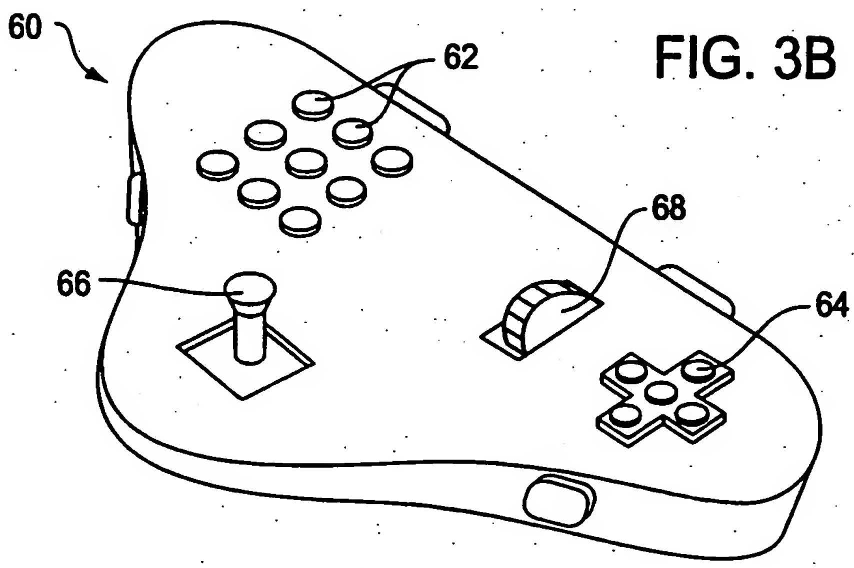


FIG. 3B



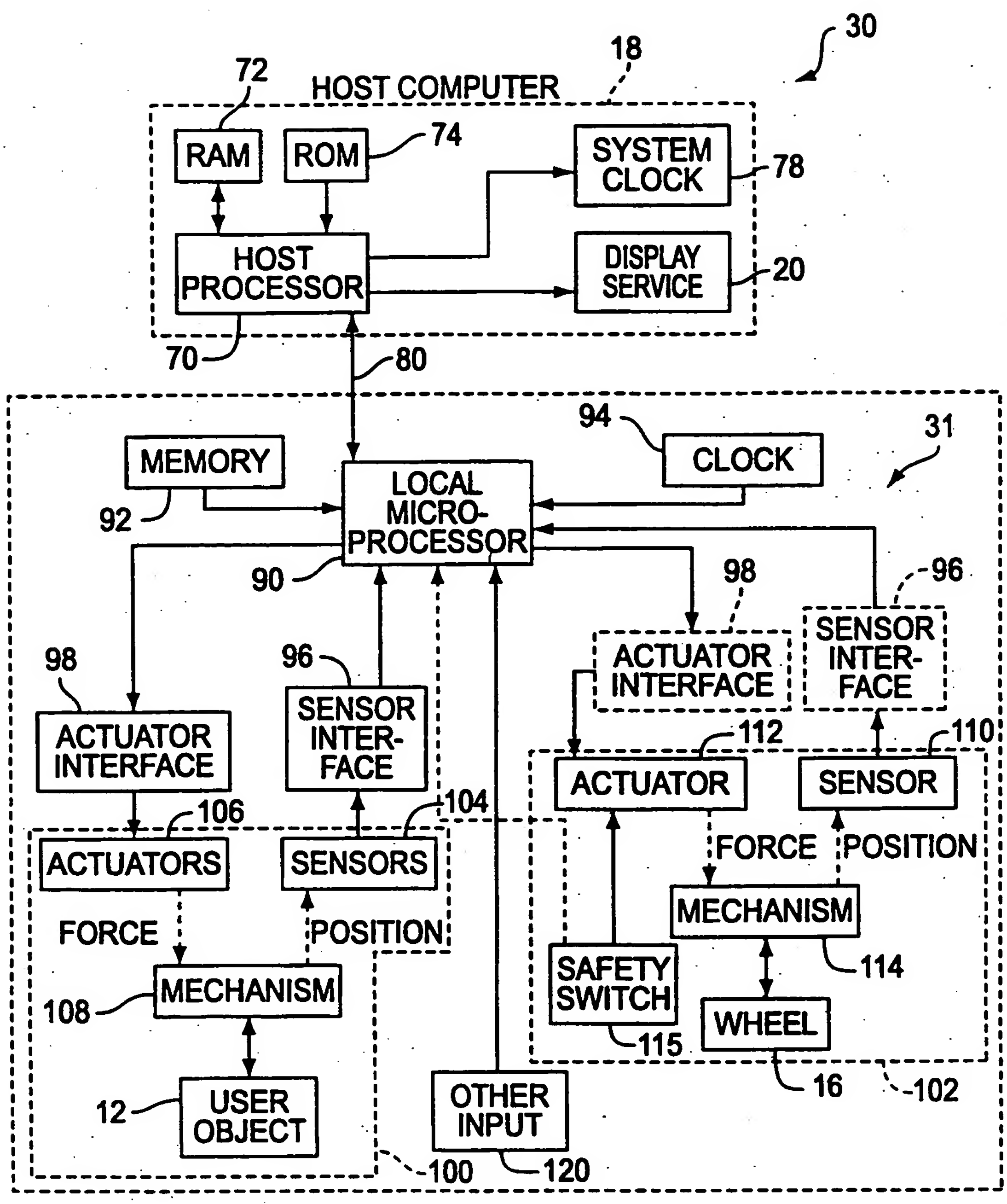

30
18
HOST COMPUTER
72
RAM
ROM
74
SYSTEM CLOCK
78
HOST PROCESSOR
DISPLAY SERVICE
20
70
80
94
CLOCK
31
MEMORY
LOCAL MICRO-PROCESSOR
92
90
98
96
ACTUATOR INTERFACE
SENSOR INTER-FACE
98
96
ACTUATOR INTERFACE
SENSOR INTER-FACE
112
110
106
104
ACTUATOR
SENSOR
ACTUATORS
SENSORS
FORCE
POSITION
FORCE
POSITION
MECHANISM
MECHANISM
114
SAFETY SWITCH
WHEEL
108
115
16
102
12
USER OBJECT
OTHER INPUT
100
120

FIG. 4

FIG. 5

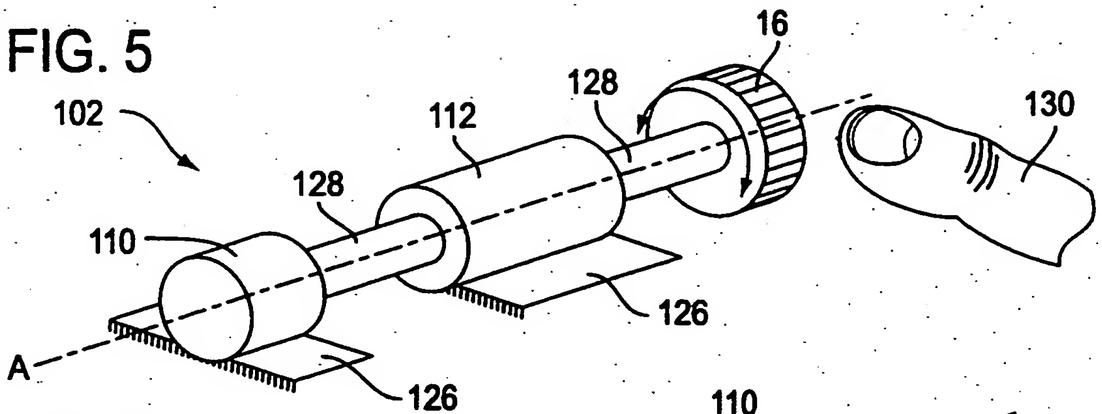


FIG. 6

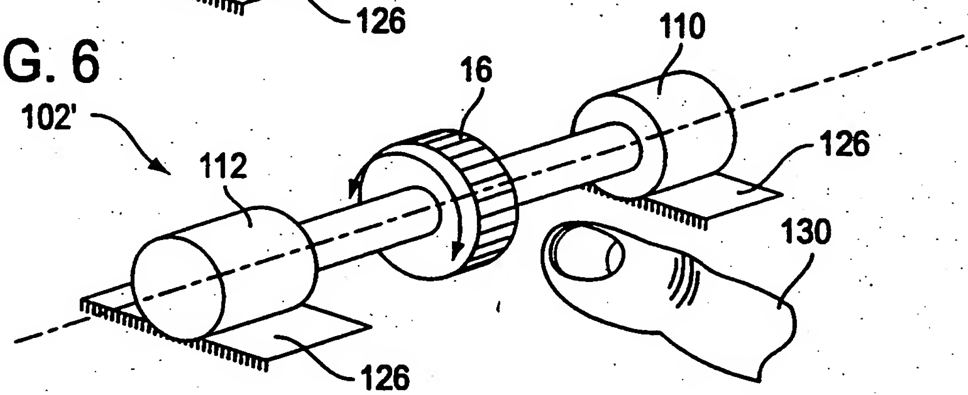


FIG. 7

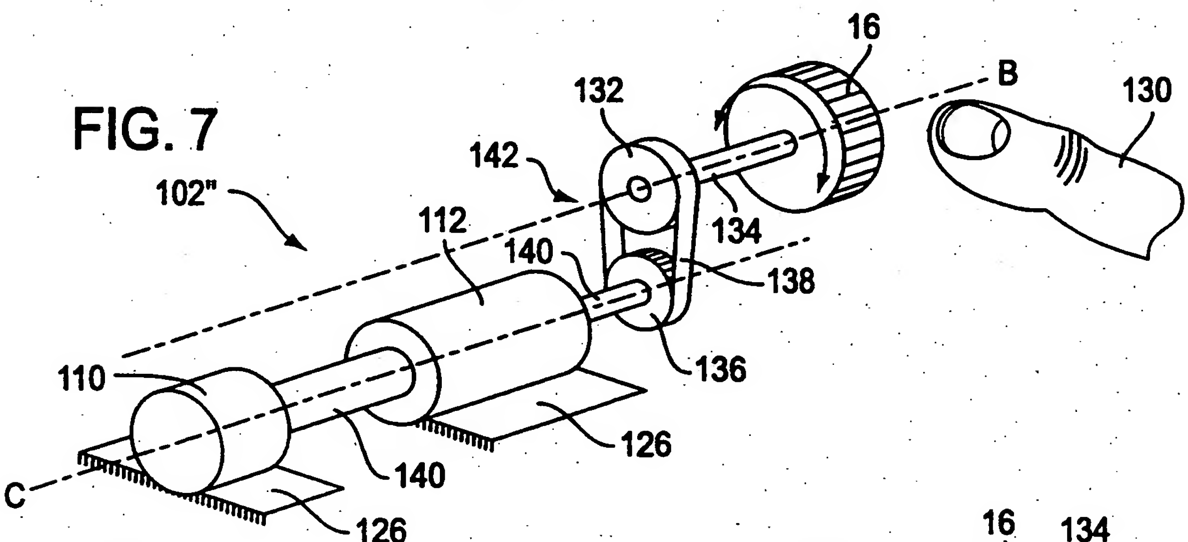
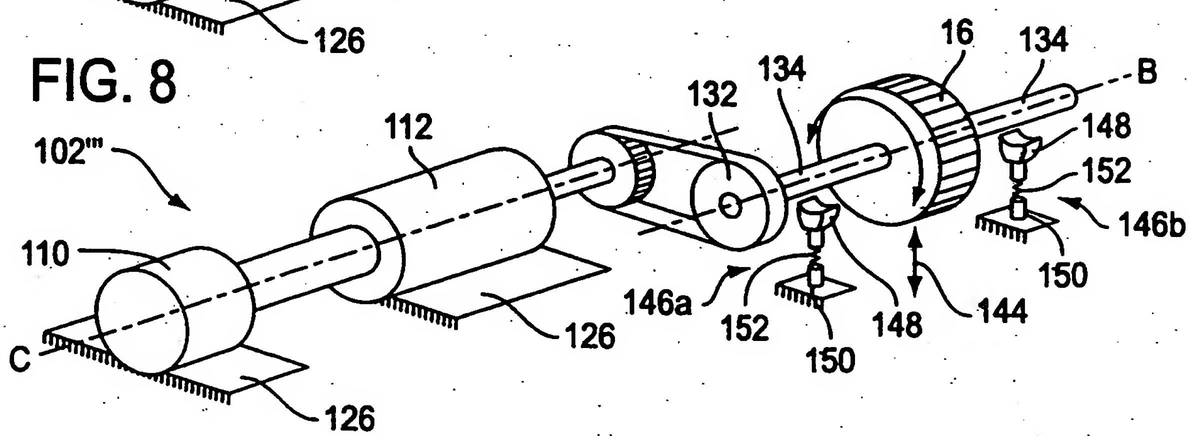


FIG. 8



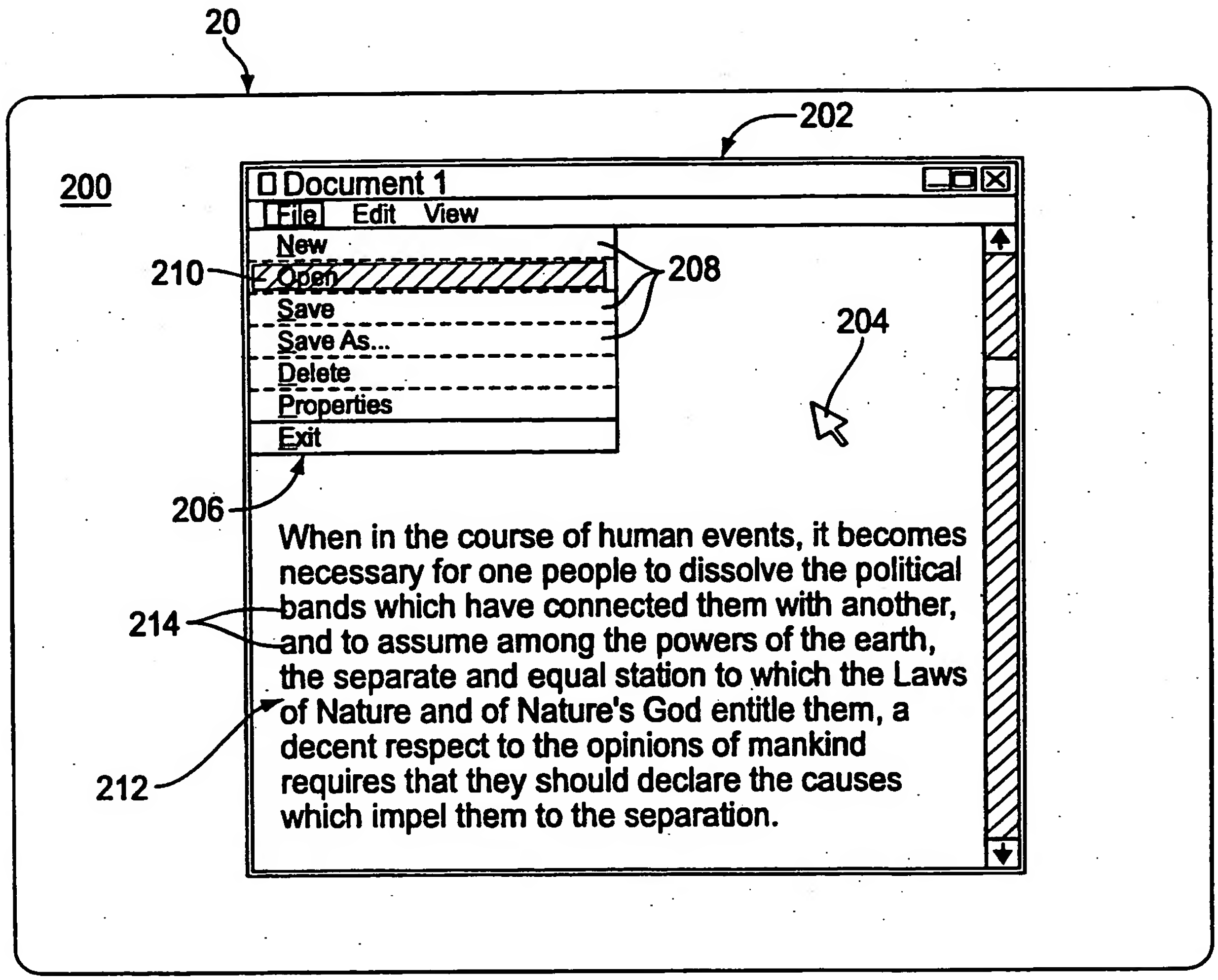

20
202
200
Document 1
File Edit View
New
Open
Save
Save As...
Delete
Properties
Exit
210
208
204
206
When in the course of human events, it becomes necessary for one people to dissolve the political bands which have connected them with another, and to assume among the powers of the earth, the separate and equal station to which the Laws of Nature and of Nature's God entitle them, a decent respect to the opinions of mankind requires that they should declare the causes which impel them to the separation.
214
212

FIG. 9

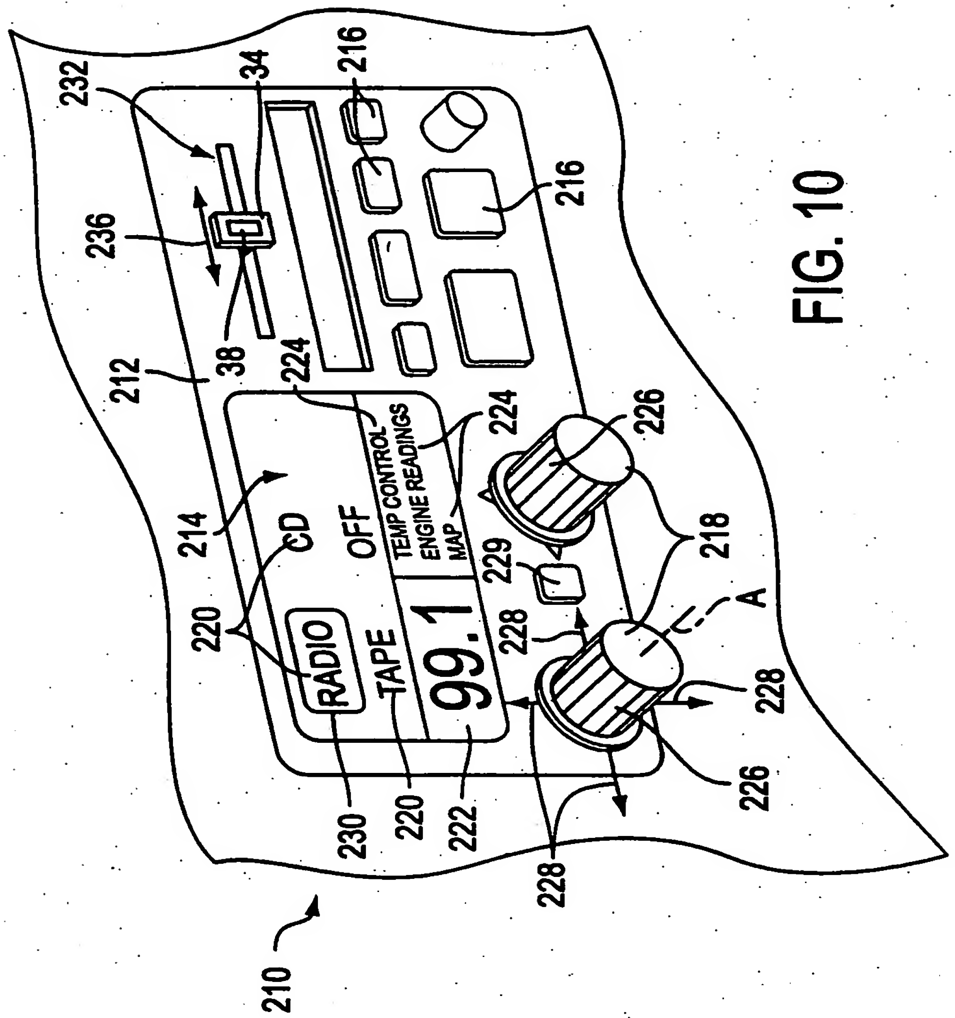


FIG. 10

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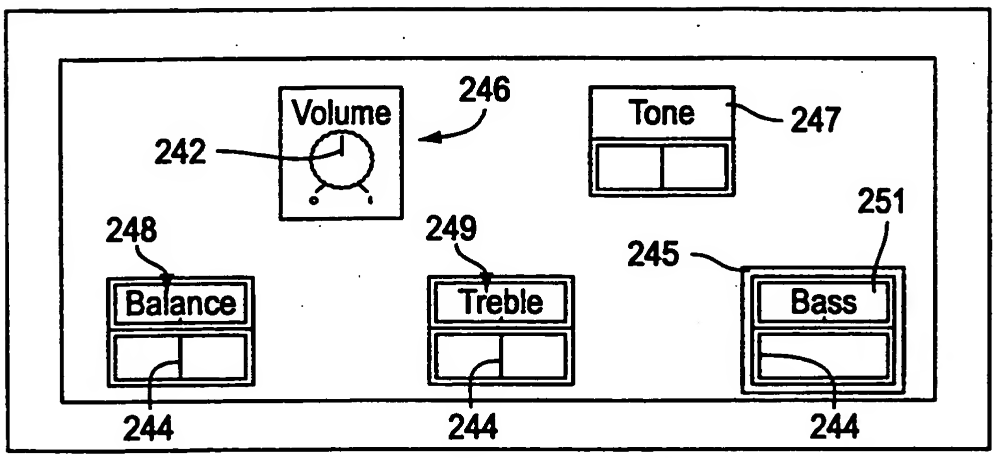
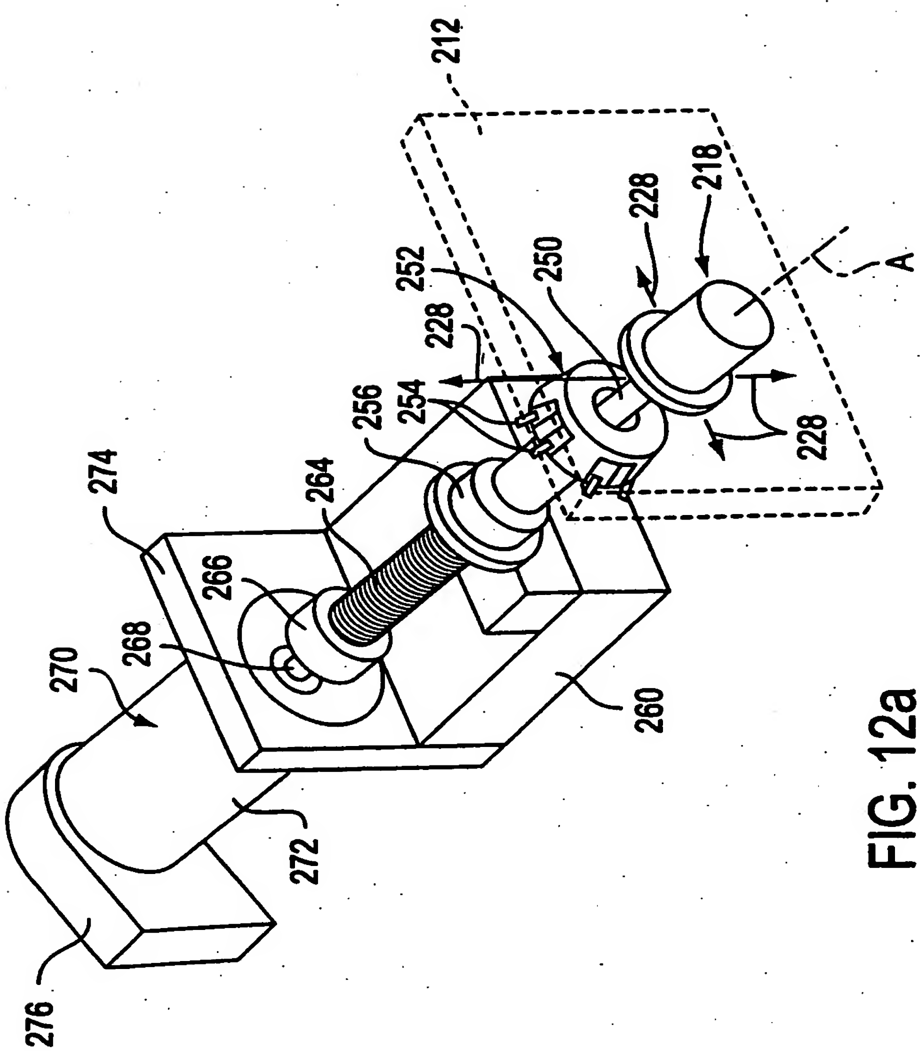

Volume
246
Tone
247
242
251
248
249
245
Balance
Treble
Bass
244
244
244

FIG. 11


212
218
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A
250
252
228
254
256
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264
274
266
268
270
260
272
276

FIG. 12a

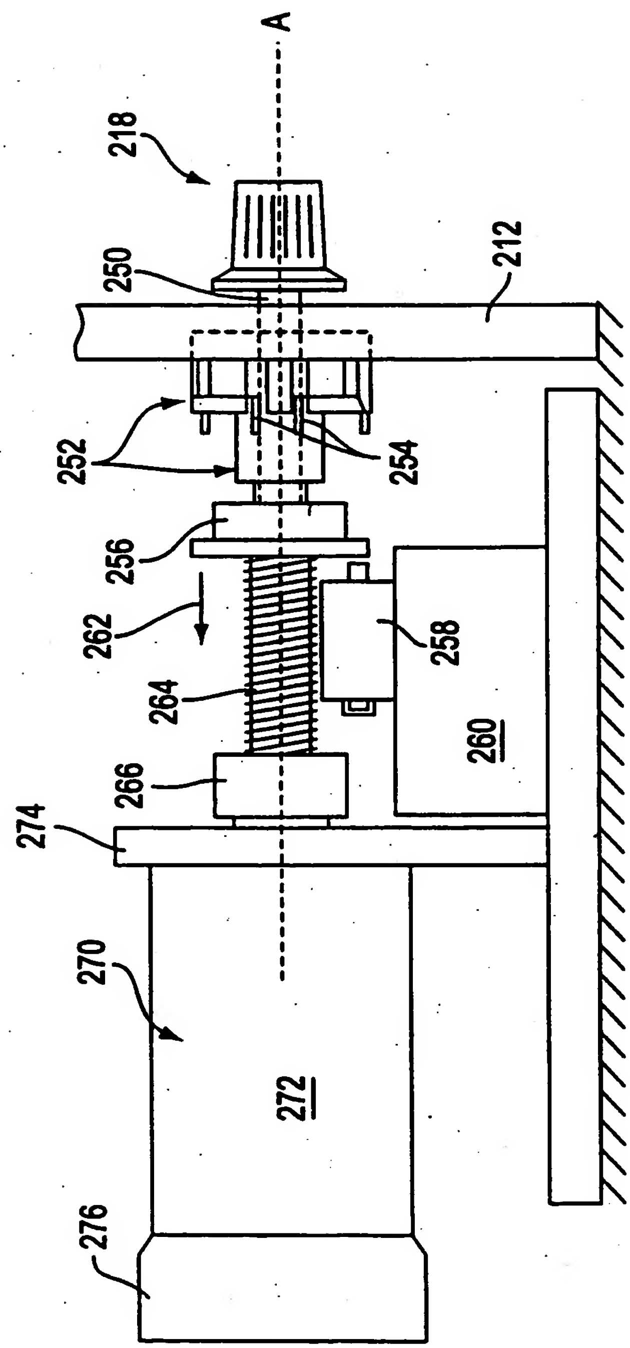


FIG. 12b

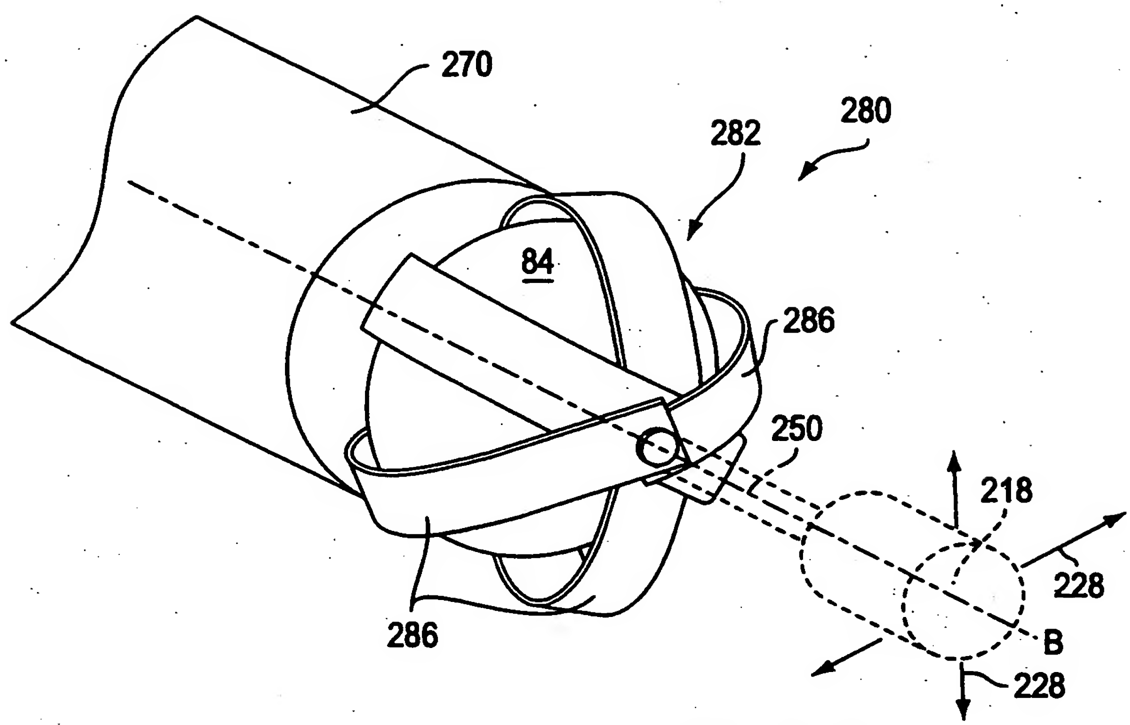


FIG. 13A

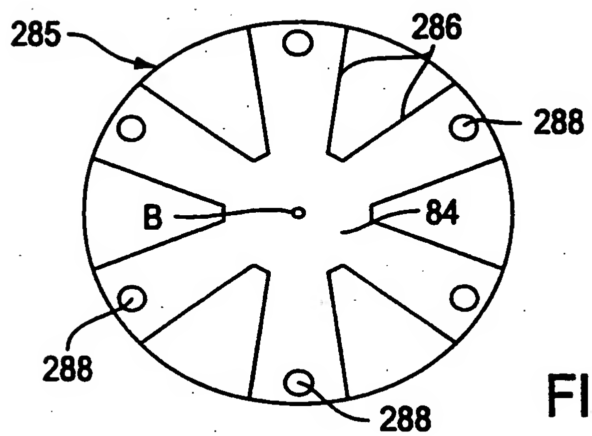


FIG. 13B

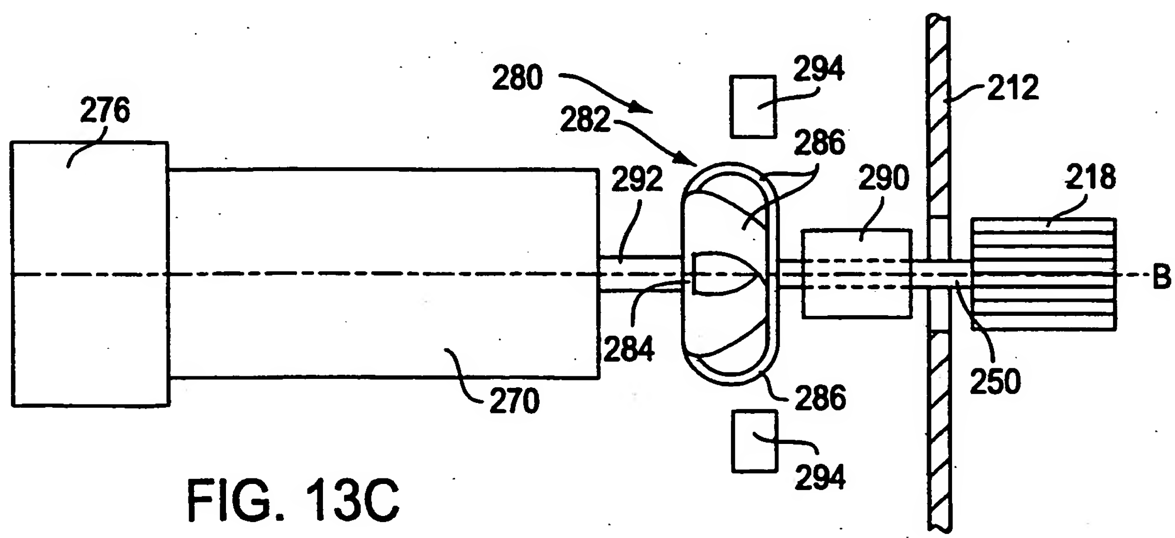
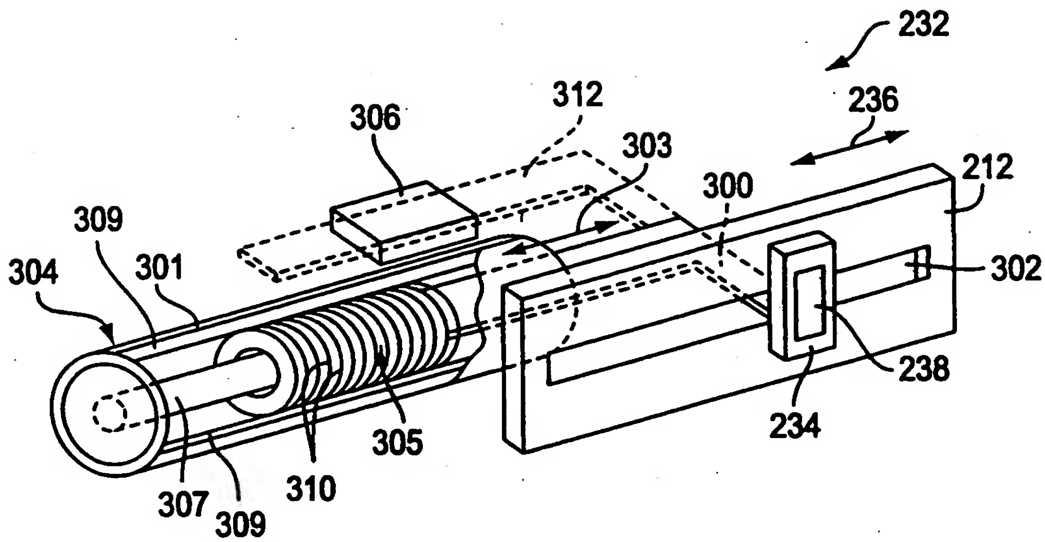


FIG. 13C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212
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307
309

FIG. 14

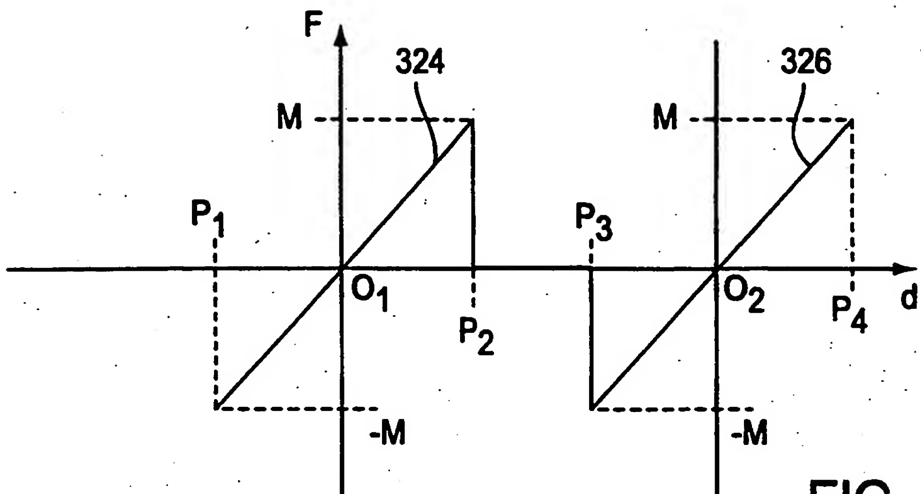

FIG. 15A

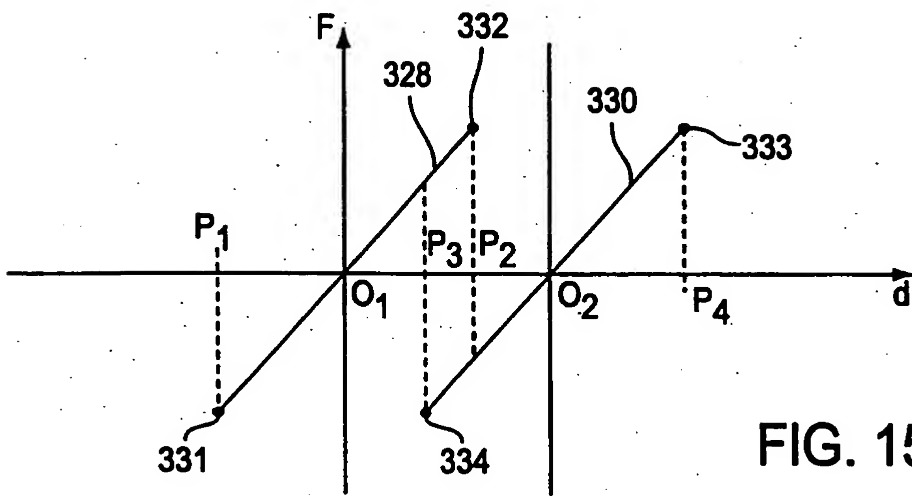

FIG. 15B

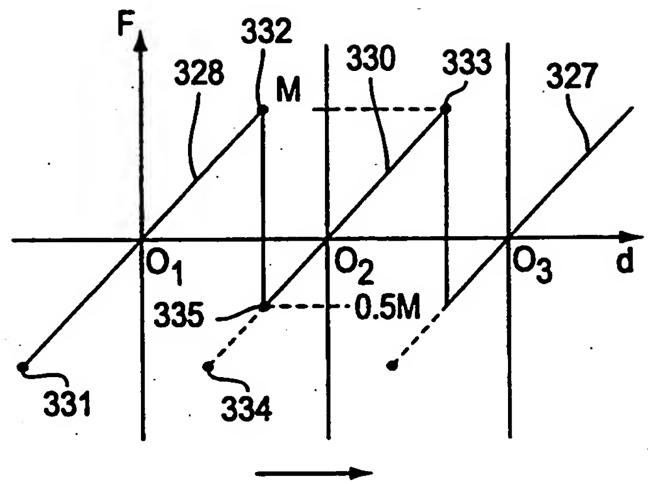

FIG. 15C

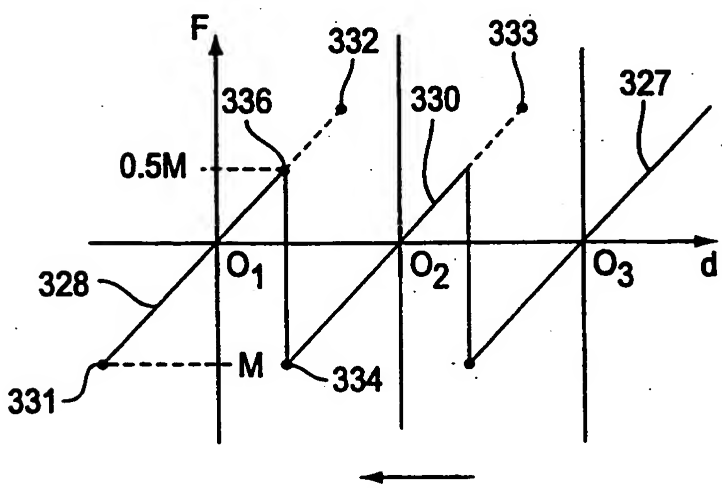

FIG. 15D

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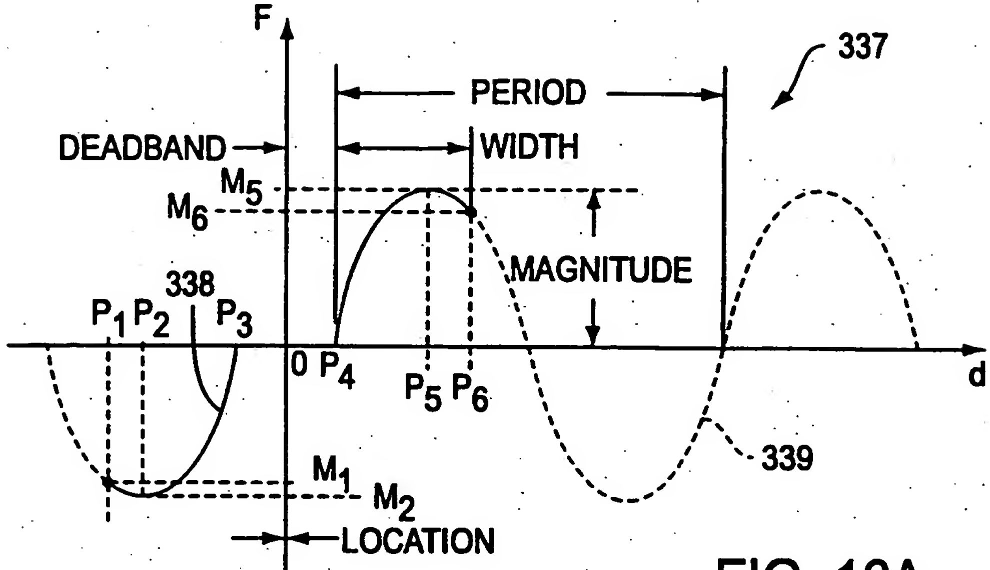

FIG. 16A

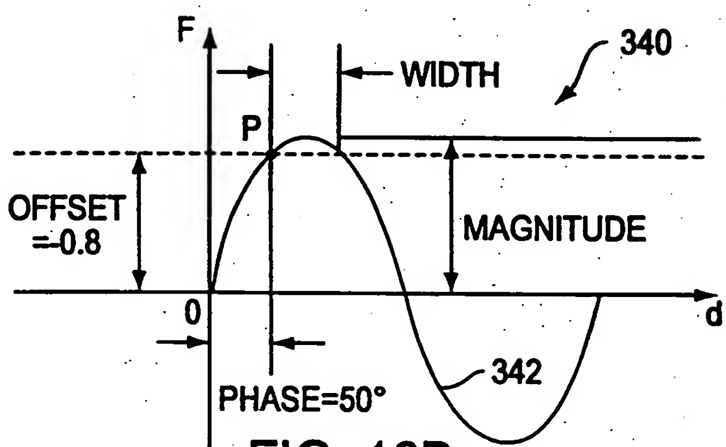

FIG. 16B

BNSDOCID: <WO_______9949443A2_I_>

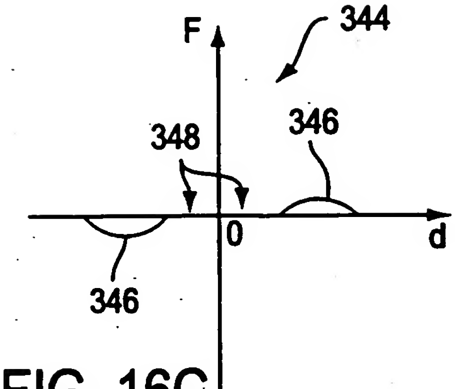

FIG. 16C

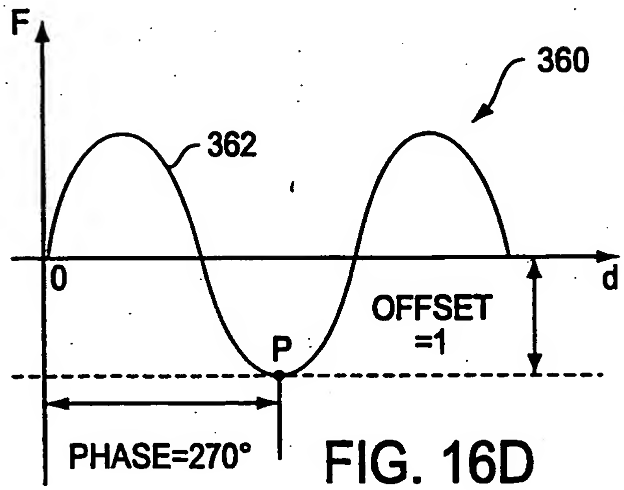

FIG. 16D

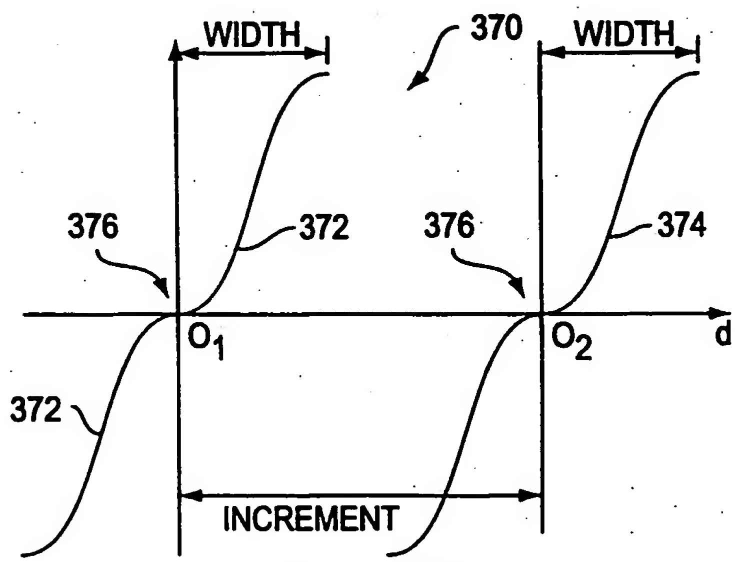

FIG. 16E

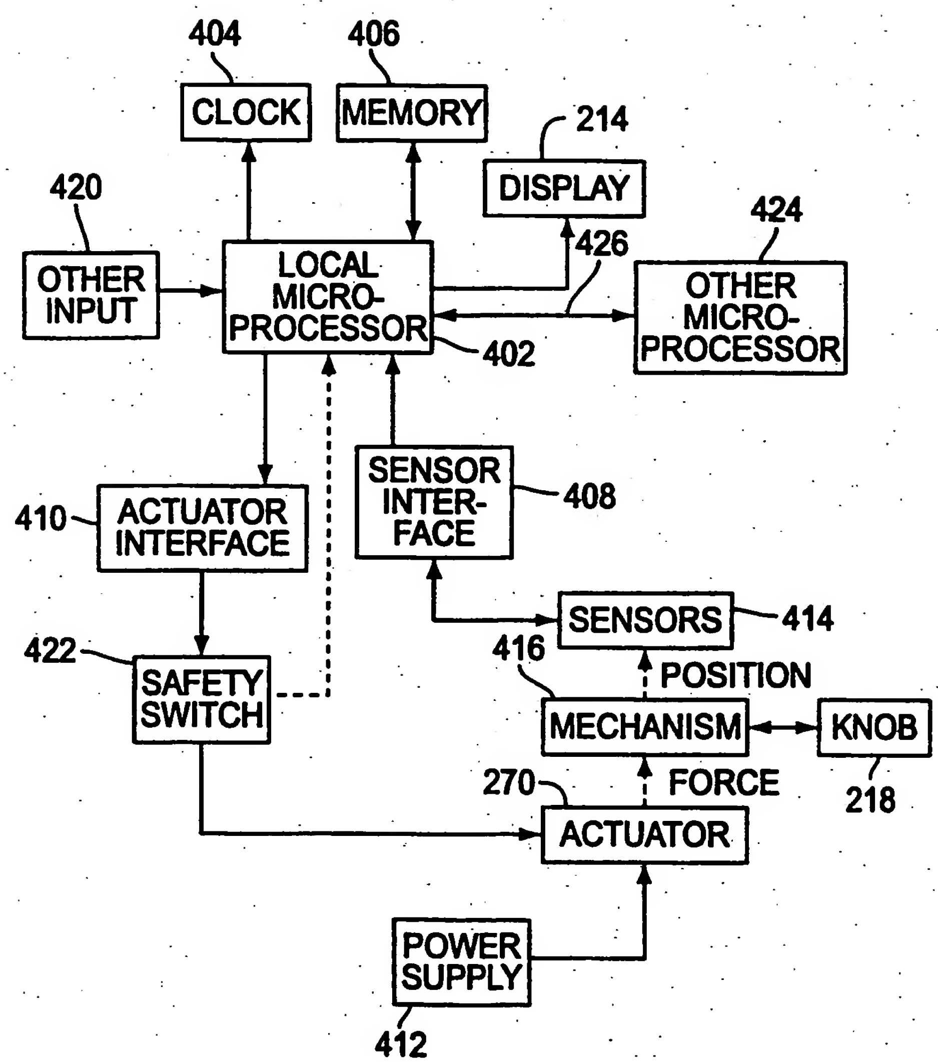

FIG. 17

BNSDOCID: <WO_______9949443A2_I_>

CORRECTED VERSION*

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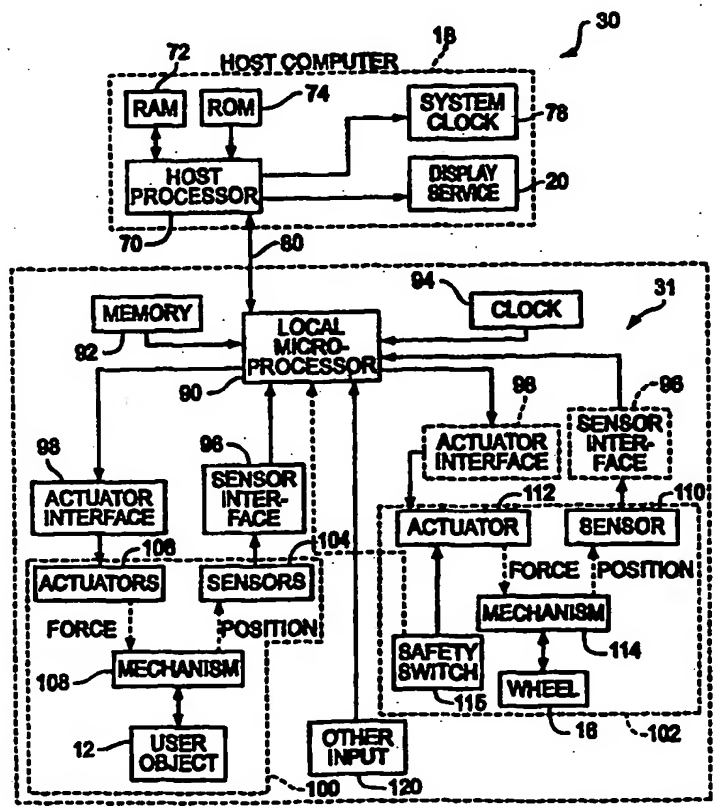
(54) Title: FORCE FEEDBACK CONTROL WHEELS AND KNOBS

(57) Abstract

A force feedback wheel or knob is provided on a mouse or other device to be manipulated by a user. In one embodiment, a rotatable wheel is mounted upon a manipulandum, such as a mouse, and rotates about a wheel axis, where a wheel sensor provides a wheel signal to a host computer indicating a rotary position of the wheel, and a wheel actuator coupled to the rotatable wheel applies a computer-modulated force to the wheel about the wheel axis. The force applied to the wheel can correspond with an event or interaction displayed in a host graphical environment. In other embodiments, a knob on a device allows a user to control functions of the device. The knob is rotatable in a rotary degree of freedom and can be moved in a transverse direction perpendicular to the axis of rotation and/or moved in a linear degree of freedom, allowing the knob to be pushed or pulled by the user. Force feedback is preferably provided using an actuator coupled to the knob. The device controlled by the knob can be, for example, an audio device, a video device, etc. Detent forces can be provided for the knob by overlapping and adjusting ranges of closely-spaced detents in the rotary degree of freedom of the knob.



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FORCE FEEDBACK CONTROL WHEELS AND KNOBS

BACKGROUND OF THE INVENTION

The present invention relates generally to interface devices for allowing humans to interface with electronic and computer devices, and more particularly to mechanical computer interface devices that allow the user to provide input to electronic systems and provide force feedback to the user.

Electronic and computer devices are used in a wide variety of applications. For many devices, a user desires to provide input to a device using a simple, intuitive mechanical control. Control wheels and knobs provide such an intuitive input device for many applications.

In one application, control wheels and knobs are useful to provide input to computer systems. For example, users can interact with a visual environment displayed by a computer on a display device to perform functions on the computer, play a game, experience a simulation or "virtual reality" environment, use a computer aided design (CAD) system, browse the World Wide Web, or otherwise influence events or images depicted on the screen. One visual environment that is particularly common is a graphical user interface (GUI). GUI's present visual images which describe various graphical metaphors of a program or operating system implemented on the computer. Common GUI's include the Windows® operating system from Microsoft Corporation, the MacOS® operating system from Apple Computer, Inc., and the X-Windows GUI for Unix operating systems. The user typically moves a user-controlled graphical object, such as a cursor or pointer, across a computer screen and onto other displayed graphical objects or screen regions, and then inputs a command to execute a given selection or operation. Other programs or environments also may provide user-controlled graphical objects such as a cursor and include browsers and other programs displaying graphical "web pages" or other environments offered on the World Wide Web of the Internet, CAD programs, video games, virtual reality simulations, etc.

A common interface device for providing user input to a GUI is a mouse or trackball. A mouse is moved by a user in a planar workspace to move a graphical object such as a cursor on the 2-dimensional display screen in a direct mapping between the position of the user manipulandum and the position of the cursor. This is typically known as "position control", where the motion of the graphical object directly correlates to motion of the user manipulandum. One drawback to traditional mice is that functions such as scrolling a document in a window and zooming a view displayed on the screen in or out are typically awkward to perform, since the user must use the cursor to drag a displayed scroll bar or click on displayed zoom controls.

These types of functions are often more easily performed by "rate control" devices, i.e. devices that have an indirect or abstract mapping of the user manipulandum to the graphical object, such as pressure-sensitive devices. Scrolling text in a window or zooming to a larger view in a window are better performed as rate control tasks, since the scrolling and zooming are not directly related to the planar position of a mouse. Similarly, the controlled velocity of a simulated vehicle is suitable for a rate control paradigm.

To allow the user easier control of scrolling, zooming, and other like functions when using a mouse, a "scroll wheel" or "mouse wheel" has been developed and has become quite common on computer mice. A mouse wheel is a small finger wheel provided on a convenient place on the mouse, such as between two mouse buttons, which the user may rotate to control a scrolling or zooming function. Most commonly, a portion of the wheel protrudes out of the top surface of the mouse which the user can move his or her finger over. The wheel typically includes a rubber or other frictional surface to allow a user's finger to easily rotate the wheel. In addition, some mice provide a "clicking" wheel that moves between evenly-spaced physical detent positions and provides discrete positions to which the wheel can be moved as well as providing the user with some physical feedback as to how far the wheel has rotated. The wheel is most commonly used to scroll a document in a text window without having to use a scroll bar, or to zoom a window's display in or out without selecting a separate zoom control. The wheel may also be used in other applications, such as a game, drawing program, or simulation.

One problem with existing mouse wheels is that they are quite limited in functionality. The wheel has a single frictional feel to it, and provides the user with very little tactile feedback as to the characteristics of the scrolling or zooming function employed. Even the mouse wheels having physical detents are limited in that the detents are spaced a constant distance apart and have a fixed tactile response, regardless of the scrolling or zooming task being performed or the characteristics of the document or view being manipulated. Providing additional physical information concerning the characteristics of the task that the wheel is performing, as well as allowing the wheel to perform a variety of other tasks in a GUI or other environment, would be quite useful to a user.

In other applications, control wheels and knobs are also quite useful. Often, rotary control knobs offer a degree of control to a user that is not matched in other forms of control devices, such as button or switch controls. For example, many users prefer to use a rotating control knob to adjust the volume of audio output from a stereo or other sound output device, since the knob allows both fine and coarse adjustment of volume with relative ease, especially compared to button controls. Both rotary and linear (slider) knobs are used on a variety of other types of devices, such as kitchen and other home appliances, video editing/playback devices, remote controls, televisions, etc.

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Some control knobs have been provided with "force feedback." Force feedback devices can provide physical sensations to the user manipulating the knob. Typically, a motor is coupled to the knob and is connected to a controller such as a microprocessor. The microprocessor receives sensor signals from the knob and sends appropriate force feedback control signals to the motor so that the motor provides forces on the knob. In this manner, a variety of programmable feel sensations can be output on the knob, such as detents, spring forces, or the like.

One problem occurring in control knobs of the prior art is that the knobs are limited to basic rotary motion. This limits the control options of the user to a simple, one-degree-of-freedom device that does not allow a variety of selection options. In addition, if force feedback is provided on the knob, the limited force feedback and control functionality of the knob limits the user from fully taking advantage of the force feedback to provide more control over desired functions.

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SUMMARY OF THE INVENTION

The present invention is directed to many embodiments involving a force feedback wheel or knob. The wheels and knobs described herein provide greater functionality and relay greater tactile information to the user concerning the control task being performed with the wheel or knob than standard non-force-feedback controls and other limited force feedback controls.

More particularly, an interface device and method for interfacing a user's input with a host computer and providing force feedback to the user includes a user manipulandum contacted and manipulated by a user and moveable in a planar workspace with respect to a ground surface. A manipulandum sensor detects a position of the user manipulandum in the planar workspace and sends a position signal to the host computer indicating a position of the user manipulandum in the workspace. A rotatable wheel is mounted upon the user manipulandum and rotates about a wheel axis, where a wheel sensor provides a wheel signal to the host computer indicating a rotary position of the wheel. A wheel actuator coupled to the rotatable wheel applies a computer-modulated force to the wheel about the wheel axis.

The user manipulandum can include a mouse object or other type of object. In a standard mouse implementation, the manipulandum sensor includes a ball and roller assembly. In a force feedback mouse implementation, one or more additional actuators are included for applying a force to the manipulandum in the workspace. A mechanical linkage having multiple members can be coupled between the manipulandum actuators and the manipulandum. The wheel can be oriented in a variety of ways; for example, the wheel can rotate about an axis parallel to the planar workspace. The wheel actuator can be directly coupled to the wheel, or can be coupled to the wheel by a drive mechanism such as a belt drive. A local microprocessor can also be provided in the interface device to control the actuator to apply the force on the wheel.

The host computer is preferably running a graphical environment, where the force applied to the wheel corresponds with an event or interaction displayed in the graphical environment. The event can be the scrolling of a displayed document as controlled by the sensed rotation of the wheel, or a zooming or panning of a view in the graphical environment. In one embodiment, the cursor's motion is influenced by the rotation of the wheel, such that the event can be an interaction of a cursor with a graphical object. Different modes, such as isotonic and isometric modes, can also be provided, where force sensations appropriate to each mode are applied to the wheel.

In a different embodiment, a force feedback wheel or knob device of the present invention provides input to an electronic device. The knob device includes a wheel rotatably coupled to a housing and rotatable about an axis, a computer-modulated actuator coupled to the wheel for generating a simulated detent sensation on the wheel, where the force detent is

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provided at a predetermined user-preferred rotational position of the wheel, and a sensor that senses rotation of the wheel and provides a wheel signal to the electronic device indicating a rotary position of the wheel. The wheel can be included on a remote control device for remotely sending signals to the electronic device, or on the housing of the electronic device itself. The electronic device can be any of a variety of devices or appliances; for example, a radio can include the force wheel for providing user-preferred detents at radio station frequencies spaced irregularly about the rotational range of the wheel.

In an embodiment of a knob controller device of the present invention, a knob is coupled to a grounded surface. The knob is rotatable in a rotary degree of freedom about an axis extending through the knob, and the knob also moveable in a transverse direction approximately perpendicular to the axis. A rotational sensor detects a position of the knob in the rotary degree of freedom, and a transverse sensor detects a position of the knob in the transverse direction. An actuator is coupled to the knob to output a force in the rotary degree of freedom about the axis, thus providing force feedback. In a preferred embodiment, the knob is moveable in multiple transverse directions. For example, the transverse sensor includes a switch that detects when the knob is moved in a transverse direction; the switch can be a hat switch having multiple individual switches, for example. In one embodiment, the knob is moveable in four transverse directions spaced approximately orthogonal to each other.

Furthermore, a local microprocessor can be included to control the force feedback on the knob. The microprocessor receives sensor signals from the rotary and transverse sensors and controls a function of a device in response to the sensor signals. The device can also include a display, wherein an image on said display is changed in response to manipulation of the knob in the transverse direction. A method of the present invention for controlling functions of a device from input provided by a knob similarly uses sensor signals from a rotary sensor and a transverse sensor to control at least one function of a device, such as adjusting a frequency of a radio tuner or updating a displayed image based on at least one of the sensor signals.

In another aspect of the present invention, a knob is coupled to a grounded surface, where the knob is rotatable in a rotary degree of freedom about an axis extending through the knob. The knob is also moveable in a linear degree of freedom approximately parallel to the axis. A rotational sensor and a linear sensor detect positions of the knob in the respective degrees of freedom. An actuator is also coupled to the knob and operative to output a force in the rotary degree of freedom about the axis, thereby providing force feedback to the knob. The linear degree of freedom of the knob allows it to be pushed and/or pulled by the user, where the push or pull motion is detected by the linear sensor. A transverse degree of freedom and a local microprocessor can also be included.

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In a different aspect of the present invention, a method for providing detent forces for a force feedback control includes outputting a first force by an actuator on a user manipulatable object, such as a rotary knob, for a first detent when the user object is moved within a range of the first detent. The first force assists movement of the user object toward an origin position of the first detent and resists movement away from the origin position. A second force for a second detent is also output on the user object when the user object is moved within a range of the second detent, similar to the first force. A portion of the range of the first detent overlaps a portion of the range of the second detent. The overlapped portions of the ranges preferably modify the second force such that a force at the beginning point of the second detent range has less magnitude than a force at an endpoint of the second detent range. Preferably, the first force and second force each have a magnitude that increases the further that the user object is positioned from that detent's origin. The direction of the knob can change the range endpoint magnitudes such that if the knob is moved in the opposite direction, the first-encountered point of the first detent range has a lesser magnitude than the last-encountered point.

In another aspect of the present invention, a method for providing detent forces for a force feedback control includes defining a periodic wave and using at least a portion of the periodic wave to define a detent force curve. The detent force curve defines a force to be output on a user manipulatable object, such as a rotary knob, based on a position of the user manipulatable object in a degree of freedom. The detent force curve is then used to command the force on the user manipulatable object as output by an actuator. The type, period and magnitude can be specified for the periodic wave. The detent force curve can be defined by specifying a portion of said periodic wave to be the width of the detent force curve, specifying a phase and an offset to be applied to said periodic wave to define the detent force curve, and/or specifying an increment distance between successive detents.

The apparatus and method of the present invention provides an interface device including a force feedback wheel or knob that allows a user to conveniently provide input to manipulate functions or events in a host computer application program or electronic device. The wheel allows substantially greater control and flexibility than previous wheels, and the force feedback allows the wheel to control a variety of useful functions in a graphical environment which prior wheels are not able to control. The linear and transverse degrees of freedom of the knob embodiment allow the user to select functions, settings, modes, or options with much greater ease and without having to take his or her hand off the knob. Force feedback detent implementations of the present invention provide overlapping detent ranges to allow more accurate control of a knob by a user within closely-spaced detents, and an efficient, convenient method for defining detents from periodic waves.

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These and other advantages of the present invention will become apparent to those skilled in the art upon a reading of the following specification of the invention and a study of the several figures of the drawing.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective view of one embodiment of a mouse interface system including a force feedback wheel of the present invention;

Figure 2 is a perspective view of a second embodiment of a force feedback mouse interface system including the force feedback wheel of the present invention;

Figures 3a and 3b are perspective views of alternate embodiments of an interface device including the force feedback wheel of the present invention;

Figure 4 is a block diagram of the interface system including a force feedback wheel of the present invention;

Figures 5 and 6 are perspective views of two embodiments of a direct drive mechanical portion of the interface device for the force feedback wheel;

Figure 7 is a perspective view of an embodiment of a belt drive mechanical portion of the interface device for the force feedback wheel;

Figure 8 is a perspective view of an embodiment of a belt drive mechanism allowing the wheel to be depressed like a button; and

Figure 9 is a diagrammatic illustration of a GUI and graphical objects which can be manipulated using the force feedback wheel of the present invention.

Figure 10 is a perspective view of one embodiment of a device including a control knob of the present invention;

Figure 11 is a diagrammatic view of a display allowing the user to use the knob of the present invention to select features of the device;

Figure 12a is a perspective view of one embodiment of the mechanism for implementing the control knob of the present invention;

Figure 12b is a side elevational view of the embodiment of Fig. 12a;

Figure 13a is a perspective view of a second embodiment of the mechanism for implementing the control knob of the present invention;

Figure 13b is a top plan view of a unitary plate used in the embodiment of Fig. 13a;

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Figure 13c is a side elevational view of the embodiment of Fig. 13a;

Figure 14 is a perspective view of a linear slider control of the present invention;

Figures 15a-15d illustrate nonoverlapping, overlapping, and hysteresis features of force detent profiles;

Figures 16a-16e are graphs illustrating the creation of detent force profiles from periodic waves according to the present invention; and

Figure 17 is a block diagram of a control system for the control knob of the present invention.

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DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIGURE 1 is a perspective view of a first embodiment of the present invention. A mouse 12 includes a force feedback mouse wheel 16 of the present invention. Mouse 12 rests on a ground surface 44 such as a tabletop or mousepad. A user grasps the mouse 12 and moves the mouse in a planar workspace on the surface 44 as indicated by arrows 22. Mouse 12 may be moved anywhere on the ground surface 44, picked up and placed in a different location, etc. A frictional ball and roller assembly (not shown) is provided on the underside of the mouse 12 to translate the motion of the mouse 12 into electrical position signals, which are sent to a host computer 18 over a bus 17 as is well know to those skilled in the art. In other embodiments, different mechanisms can be used to convert mouse motion to position or motion signals received by the host computer. It should be noted that the term "mouse" as used herein indicates an object 12 generally shaped to be grasped or contacted by a user from above and moved within a substantially planar workspace (and additional degrees of freedom if available). Typically, a mouse is a smoothly- or angular-shaped compact unit that snugly fits under a user's hand, fingers, and/or palm, but can be implemented as other objects as well.

Mouse 12 includes buttons 15 and a mouse wheel 16. Buttons 15 can be pressed by the user to provide an associated signal to the host computer 18 over bus 17. Additional buttons can be provided in other embodiments of mouse 12. Mouse wheel 16 of the present invention is provided, for example, between buttons 15 to allow easy access for a user's finger. A wheel 16 can alternatively or additionally be provided in a location easily accessed by the user's thumb. The wheel as shown only partially protrudes from an aperture 13 in the housing of the mouse 12 and preferably is provided with a frictional surface, such as a rubber-like surface or a series of ridges or bumps to allow the user's finger to grip the wheel more easily. Wheel 16 is operative to rotate in place in when the user's finger pushes the wheel in either rotational direction. When the user rotates the wheel, a corresponding signal indicating the amount of rotation and the direction of rotation is sent to host computer 18 over bus 17. For example, the wheel signal can be used by host computer to scroll a document in a window, pan a view, or zoom a view. The wheel 16 is coupled to an actuator in mouse 12 which applies forces to wheel 16, which is described in greater detail below. Typically, wheel 16 is provided in a Y-orientation and rotates about an axis oriented in the X-direction as shown in Figure 1, where the wheel controls vertical (Y-direction) motion of a graphical object displayed by host 18. In other embodiments, a wheel can be provided in an X-orientation that rotates about a Y-axis, and which can control horizontal (X-direction) motion of a host graphical object. In yet other embodiments, two or more wheels 16 can be provided on mouse 12 in different orientations to provide the user with multiple wheel controls. In still other embodiments, wheel 16 can be provided as a trackball (or similar

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approximately spherical object) provided in a socket in mouse 12, and which can be moved in both X- and Y- directions and have forces applied thereto.

Furthermore, in some embodiments, wheel 16 may be depressed by the user as indicated by arrow 19. The wheel, when pressed, causes contacts to be electrically connected and provides a signal to host computer 18. Wheel 16 thus can also operate as an additional mouse button 15. A mechanical/electrical interface (not shown) is preferably included to sense manipulations of the wheel 16 and transmit force to the wheel. In the preferred embodiment, power is provided to actuators over bus 17 (e.g. when bus 17 includes a USB interface). The structure and operation of wheel 16 and the interface is described in greater detail with respect to Figures 5-9.

Host computer 18 is preferably a personal computer or workstation, such as an IBM-PC compatible computer or Macintosh personal computer, or a SUN or Silicon Graphics workstation. For example, the computer 18 can operate under the Windows™ or MS-DOS operating system in conformance with an IBM PC AT standard. Alternatively, host computer system 18 can be one of a variety of home video game systems commonly connected to a television set, such as systems available from Nintendo, Sega, or Sony. In other embodiments, host computer system 18 can be a "set top box" which can be used, for example, to provide interactive television functions to users, or a "network-" or "internet-computer" which allows users to interact with a local or global network using standard connections and protocols such as used for the Internet and World Wide Web. Host computer preferably includes a host microprocessor, random access memory (RAM), read only memory (ROM), input/output (I/O) circuitry, and other components of computers well-known to those skilled in the art.

Host computer 18 preferably implements a host application program with which a user is interacting via mouse 12 and other peripherals, if appropriate. The application program includes force feedback functionality to provide appropriate force signals to mouse 12. For example, the host application program can be a GUI, simulation, video game, Web page or browser that implements HTML or VRML instructions, scientific analysis program, virtual reality training program or application, or other application program that utilizes input of mouse 12 and outputs force feedback commands to the mouse 12. Herein, for simplicity, operating systems such as Windows™, MS-DOS, MacOS, Unix, etc. are also referred to as "application programs." In one preferred embodiment, an application program utilizes a graphical user interface (GUI) to present options to a user and receive input from the user. Herein, computer 18 may be referred as displaying "graphical objects" or "computer objects." These objects are not physical objects, but are logical software unit collections of data and/or procedures that may be displayed as images by computer 18 on display screen 20, as is well known to those skilled in the art. A displayed cursor, a view displayed by a GUI window, a portion of a document displayed in the window, or a simulated cockpit of an aircraft can all be considered graphical objects. The host application program checks for input signals received from the mouse 12, displays updated

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graphical objects and other events as appropriate, and outputs force signals across bus 17 to mouse 12 to control forces output on wheel 16, as described in greater detail below. In alternate embodiments, a separate local microprocessor can be included in mouse 12 to locally control force output on wheel 16. Such a microprocessor can be provided in embodiments, such as the embodiment of Figure 1, having no other force feedback except through wheel 16. A local microprocessor is described in greater detail with respect to Figure 4.

Display device 20 is typically included in host computer 18 and can be a standard display screen (LCD, CRT, etc.), 3-D goggles, or any other visual output device. Typically, the host application provides images to be displayed on display device 20 and/or other feedback, such as auditory signals. For example, display screen 20 can display images from a GUI. Images describing a first person point of view can be displayed, as in a virtual reality game or simulation. Or, images describing a third-person perspective of objects, backgrounds, etc. can be displayed.

Mouse 12 can be used, for example, to control a computer-generated graphical object such as a cursor or pointer displayed in a graphical computer environment, such as a GUI. The user can move the mouse in 2D planar workspace to move the cursor to graphical objects in the GUI or perform other tasks. The user may use wheel 16 to scroll text documents, perform zooming functions on views in windows, perform panning functions, or perform other rate control tasks. Forces output on wheel 16 provide information about the rate control task performed by the wheel, and allow the user to perform additional control functions as described with reference to Figure 9. For example, the computer system may provide force feedback commands to the wheel when the user moves the graphical object against a generated surface such as an edge of a window, a virtual wall, etc. It thus appears and feels to the user that the graphical object is contacting a real surface. In some embodiments, the user may influence the movement of the cursor with the rotation of wheel 16. In other graphical environments, such as a virtual reality video game, a user can be controlling a computer player or vehicle in the virtual environment by manipulating the mouse 12 and wheel 16.

There are two primary "control paradigms" of operation for mouse 12: position control and rate control. Position control is the more typical control paradigm for mouse and similar controllers, and refers to a mapping of mouse 32 in which displacement of the mouse in physical space directly dictates displacement of a graphical object. Under a position control mapping, the computer object does not move unless the user manipulandum is in motion. Also, "ballistics" or other non-linear adjustments to cursor position can be used, in which, for example, small motions of the mouse have a different scaling factor for cursor movement than large motions of the mouse, to allow more control of small cursor movement. As shown in Figure 1, the host computer may have its own "host frame" 28 which is displayed on the display screen 20. In contrast, the mouse 12 has its own "local frame" 30 in which the mouse 12 is moved. In a

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position control paradigm, the position (or change in position) of a user-controlled graphical object, such as a cursor, in host frame 30 corresponds to a position (or change in position) of the mouse 12 in the local frame 28.

Rate control is also used as a control paradigm. This refers to a mapping in which the displacement of a user manipulandum along one or more provided degrees of freedom is abstractly mapped to motion or rate of a computer-simulated object under control. There is not a direct physical mapping between physical object (mouse) motion and computer object motion.

The mouse 12 is useful for both position control ("isotonic") tasks and rate control ("isometric") tasks. For example, as a traditional mouse, the position of mouse 12 in its local frame 30 workspace can be directly mapped to a position of a cursor in host frame 28 on display screen 20 in a position control paradigm. Also, the mouse wheel 16 can be rotated in its degree of freedom against an opposing output force to command rate control tasks in an isometric mode. Wheel 16 can also be used for position control tasks, as described in greater detail below.

FIGURE 2 is a perspective view of a second embodiment 30 of a mouse device using the force feedback mouse wheel 16 of the present invention. Force feedback mouse interface system 30 is capable of providing input to a host computer based on the user's manipulation of the mouse and capable of providing force feedback to the system based on events occurring in a program implemented by the host computer. Mouse device 30 includes added force feedback functionality over the embodiment 12 of Figure 1 in that the planar degrees of freedom of mouse 32 are provided with force feedback in addition to the wheel 16 being provided with force feedback. Mouse system 30 includes an interface device 31 including a mouse 32 and an interface 34; and a host computer 18.

Mouse 32, similar to mouse 12 of Figure 1, is an object that is preferably grasped or gripped and manipulated by a user. In the described embodiment, mouse 32 is shaped so that a user's fingers or hand may comfortably grasp the object and move it in the provided degrees of freedom in physical space. One or more buttons 15 allow the user to provide additional commands to the computer system. A thumb button (not shown) can also be provided on mouse 32. One or more of the buttons 15 may command specific force feedback features of the system 30, as described below. Mouse 32 is preferably supported upon a grounded pad 42, which is supported by grounded surface 44.

It will be appreciated that a great number of other types of user manipulandums ("user manipulatable objects" or "physical objects") can be used with the method and apparatus of the present invention in place of or in addition to mouse 32. For example, such objects may include a sphere, a puck, a joystick, cubical- or other-shaped hand grips, a receptacle for receiving a finger or a stylus, a flat planar surface like a plastic card having a rubberized, contoured, and/or

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bumpy surface, or other objects. Other examples of a user object 32 are described below with reference to Figures 3a and 3b.

Mouse 32 (or other manipulandum) is also provided with a mouse wheel 16 as described with reference to Figure 1. Mouse wheel 16 is provided with force feedback separately from the mouse 32, e.g. an actuator separate from actuators that drive mouse 32 can be used to provide forces on wheel 16. The functions controlled by wheel 16 can be independent of the functions controlled by the planar movement of mouse 32 in its workspace. Alternatively, the functions controlled by wheel 16 can be synchronized or added to functions controlled by planar mouse movement, as described in greater detail below. Wheels 16 in different orientations, or multiple wheels or a trackball, can be provided on mouse 32 as described with reference to mouse 12.

Interface 34 is provided in a housing 33 of the mouse interface device 31 and interfaces mechanical and electrical input and output between the mouse 32 and host computer 18. Interface 34 provides multiple degrees of freedom to mouse 32; in the preferred embodiment, two linear, planar degrees of freedom are provided to the mouse, as shown by arrows 22. In other embodiments, greater or fewer degrees of freedom can be provided, as well as rotary degrees of freedom. A mechanical linkage (not shown) preferably couples the mouse 32 to sensors and actuators of the device 31; some examples of such a linkage are described in copending PCT application WO 98/24183, incorporated by reference herein.

In a preferred embodiment, the user manipulates mouse 32 in a planar workspace, and the position of mouse 32 is translated into a form suitable for interpretation by position sensors of the interface 34. The sensors track the movement of the mouse 32 in planar space and provide suitable electronic signals to an electronic portion of interface 34. The interface 34 provides position information to host computer 18. An electronic portion of interface 34 may be included within the housing 33 to provide electronic signals to host computer 18, as described below with reference to Figure 4. In addition, host computer 18 and/or interface 34 provide force feedback signals to actuators coupled to interface 34, and actuators generate forces on members of the mechanical portion of the interface 34 to provide forces on mouse 32 in provided or desired degrees of freedom and on wheel 16 in its rotary degree of freedom. The user experiences the forces generated on the mouse 32 as realistic simulations of force sensations such as jolts, springs, textures, "barrier" forces, and the like.

The interface 34 can be coupled to the computer 18 by a bus 37, which communicates signals between interface 34 and computer 18 and also, in the preferred embodiment, provides power to the interface 34 (e.g. when bus 17 includes a USB interface). In other embodiments, signals can be sent between interface 34 and computer 18 by wireless transmission/reception. The interface 34 can also receive inputs from other input devices or controls that are associated with mouse system 30 and can relay those inputs to computer 18, such as buttons 15.

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Host computer 18 is described above with reference to Figure 1. The host application program checks for input signals received from the mouse 32, and outputs force values and/or commands to be converted into forces on mouse 32 and on wheel 16. Suitable software drivers which interface force feedback application software with computer input/output (I/O) devices are available from Immersion Human Interface Corporation of San Jose, California.

Mouse system 30 can be used for both position control and rate control. Under a position control mapping, the positions of mouse 32 and a graphical object such as a cursor are directly mapped, as in normal mouse operation. "Ballistics", as described above, can also be provided, and these adjustments can be used in mouse system 30 if desired. Mouse system 30 can also provide a rate control mode in which the displacement of mouse 32 in a particular direction against an opposing output force can command rate control tasks in an isometric mode, as described in U.S. Patent no. 5,825,308, incorporated by reference herein. Furthermore, mouse wheel 16 can also control position and/or rate control tasks independently of the position of the mouse 32 in its workspace, as described in greater detail below.

The mouse system 10 can also include an indexing function or "indexing mode" which allows the user to redefine the offset between the positions of the mouse 32 in the local frame 30 and a user-controlled graphical object, such as a cursor, in the host frame 28. A hand weight safety switch can also be provided as described in greater detail in patent 5,825,308. Other features of the present invention are also provided using force feedback functionality. For example, a thumb button (not shown) or other button 15 can toggle a force functionality mode in which designated graphical objects or regions displayed on screen 20 have other functions enabled by force feedback to wheel 16. This is described in greater detail with respect to Figure 9.

FIGURES 3a and 3b illustrate other embodiments of an interface device and user manipulandum which can incorporate the features of the present invention. In Figure 3a, a hand-held remote control device 50 can be used to access the functions of an electronic device or appliance remotely by a user. For example, remote control 50 can be used to select functions of a television, video cassette recorder, sound stereo system, home computer, kitchen appliance, etc. Such control devices typically provide wireless operation by transmitting input signals using an electromagnetic beam that is detected by a detector on the electronic device. Or, remote control 50 can select functions of an internet or network computer connected to a television. For example, one popular device is Web-TV™, which is connected to a television and displays internet information such as web pages on the television screen. Remote control 50 may include buttons 52 for selecting options of the device or appliance, of the application program running on the device, of web pages, etc. Herein, the term "electronic device" is intended to include all such devices as well as a host computer 18 as described above.

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Remote control 50 also includes a control knob 54 (which is also considered a "wheel" as referenced herein). Knob 54 can be oriented with an axis of rotation approximately perpendicular to the surface of the device 50, as shown in Fig. 3a. Alternatively, the knob 54 can be oriented similarly to the mouse wheel 16, with the axis of rotation approximately parallel to the device surface. Knob 54 is provided with force feedback similarly to the mouse wheel 16 described with reference to Figures 1 and 2 to control a variety of functions of the controlled device or appliance, where the force feedback is integrally implemented with the control functions. For example, force detents can be provided by an actuator on knob 54, which are forces that attract the knob to a particular rotational position and resist movement of the knob away from that position. The position can correspond to a particular network or station broadcast on the television, thus making channel selection easier for the user. Alternatively, a force detent does not provide attraction or repulsive forces, but instead provides a force "bump" to indicate a particular position on the knob has been rotated past. Additional knobs with such detents can be provided for additional functions, such as volume control for sound speakers, fast forward or rewind of a video cassette recorder or computer-displayed movie (such as a DVD movie), scrolling a displayed document or web page, etc. Alternatively, a single knob 54 can be used for a variety of different functions, where the function of the knob (volume, channel selection, etc.) can be selected with a separate button or switch.

Another type of force sensation that can be output on knob 54 is a spring force. The spring force can provide resistance to rotational movement of the knob in either direction to simulate a physical spring on the knob. This can be used, for example, to "snap back" the knob to its rest or center position after the user lets go of the knob, e.g. once the knob is rotated past a particular position, a function is selected, and the user releases the knob to let the knob move back to its original position. An isometric rate-control mode for use with such a spring force is described below. A damping force sensation can also be provided on knob 54 to slow down the rotation of the knob, allowing more accurate control by the user. Furthermore, any of these force sensations can be combined together for a single knob 54 to provide multiple simultaneous force effects. Other forces usable with knob 54 are described in greater detail below with respect to Figure 9.

Knob 54 can similarly be provided directly on a radio, tuner, amplifier, or other electronic device, rather than on remote control 50. For example, a radio in a car that includes knob 54 can use force feedback "snap-to" detents for the favorite station frequencies preprogrammed by the user. This is convenient since the preferred radio frequencies are most likely spaced at irregular intervals in the radio frequency range; the ability to program the detents at any location in the range is desired. In addition, the knob can be moved by the actuators to select the nearest preprogrammed station, or a wide variety of different force sensations can be output. Furthermore, as described above, the detects can be used for different functions on the

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same knob, such as volume, tone, balance, etc. Alternatively, different sets of detent force profiles can be stored in a memory device on the radio and a particular set can be provided on the knob 54 by a microprocessor in the radio.

Figure 3b shows another embodiment in which a gamepad controller 60 is provided with a force feedback wheel. Controller 60 is intended to be held by both hands of a user. The controller 60 can include the standard input devices of game controllers, such as buttons 62, a directional game pad 64, and a fingertip joystick 66. The joystick 66 can in some embodiments be provided with force feedback. A finger wheel 68 can also be provided on controller 60 at any of various locations on the controller. Wheel 68 can operate similarly to the mouse wheel 16 described with reference to Figures 1 and 2, or to the knob 54 described with reference to Figure 3a. For example, wheel 68 can operate as a throttle or thrust control in a game for a simulated vehicle and include force feedback in an isometric mode or isotonic mode, or the wheel can be used to guide a pointer or other object on the screen.

FIGURE 4 is a block diagram illustrating an interface of the mouse system 30 of Figure 2 suitable for use with the present invention. Mouse system 30 includes a host computer 18 and interface device 31. A similar force feedback system including many of the below components is described in detail in U.S. patent nos. 5,734,373 and 5,825,308, which are incorporated by reference herein in their entirety.

Host computer 18 is preferably a personal computer, workstation, video game console, or other computing or display device, as explained with reference to Figure 1. Host computer system 18 commonly includes a host microprocessor 70, random access memory (RAM) 72, read-only memory (ROM) 74, a clock 78, and a display device 20. Host microprocessor 70 can include a variety of available microprocessors from Intel, AMD, Motorola, or other manufacturers. Microprocessor 108 can be single microprocessor chip, or can include multiple primary and/or co-processors. Microprocessor 108 preferably retrieves and stores instructions and other necessary data from RAM 72 and ROM 74 as is well known to those skilled in the art. In the described embodiment, host computer system 18 can receive sensor data or a sensor signal via a bus 80 from sensors of system 10 and other information. Microprocessor 70 can receive data from bus 120 using I/O electronics, and can use the I/O electronics to control other peripheral devices. Host computer system 18 can also output commands to interface device 31 via bus 120 to cause force feedback.

Clock 78 is a standard clock crystal or equivalent component which can be used by host computer 18 to provide timing to electrical signals used by host microprocessor 70 and other components of the computer system 18. Display device 20 is described with reference to Figure 1. Other types of peripherals can also be coupled to host processor 70, such as storage devices

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(hard disk drive, CD ROM drive, floppy disk drive, etc.), printers, audio output devices, and other input and output devices.

Interface device 31 is coupled to host computer system 18 by a bi-directional bus 120. The bi-directional bus sends signals in either direction between host computer system 18 and the interface device 104. Bus 120 can be a serial interface bus providing data according to a serial communication protocol, a parallel bus using a parallel protocol, or other types of buses. An interface port of host computer system 18 connects bus 120 to host computer system 18. In another embodiment, an additional bus can be included to communicate between host computer system 18 and interface device 11. One preferred serial interface bus used in the present invention is the Universal Serial Bus (USB). USB can also source power to drive actuators 64 and other devices of device 31.

The electronic portion of interface device 31 includes a local microprocessor 90, local clock 92, local memory 94, sensor interface 96, and actuator interface 98. Additional electronic components may also be included for communicating via standard protocols on bus 120. These components can be included in device 31 or host computer 18 if desired.

Local microprocessor 90 preferably coupled to bus 120 and is considered "local" to interface device 31, where "local" herein refers to processor 90 being a separate microprocessor from any processors 70 in host computer 18, and to processor 90 being dedicated to force feedback and sensor I/O of the interface device 31. Microprocessor 90 can be provided with software instructions to wait for commands or requests from host computer 18, parse/decode the command or request, and handle/control input and output signals according to the command or request. In addition, processor 90 preferably operates independently of host computer 18 by reading sensor signals and calculating appropriate forces from those sensor signals, time signals, and force processes selected in accordance with a host command, and output appropriate control signals to the actuators. Suitable microprocessors for use as local microprocessor 90 include the 8X930AX by Intel, the MC68HC711E9 by Motorola and the PIC16C74 by Microchip, for example. Microprocessor 90 can include one microprocessor chip, or multiple processors and/or co-processor chips, and can include digital signal processor (DSP) functionality. Also, "haptic accelerator" chips can be provided which are dedicated to calculating velocity, acceleration, and/or other force-related data.

For example, in one host-controlled embodiment that utilizes microprocessor 90, host computer 18 can provide low-level force commands over bus 120, which microprocessor 90 directly transmits to the actuators. In a different local control embodiment, host computer system 18 provides high level supervisory commands to microprocessor 90 over bus 120, and microprocessor 90 manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer 18. In the local control

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embodiment, the microprocessor 90 can independently process sensor signals to determine appropriate output actuator signals by following the instructions of a "force process" that may be stored in local memory and includes calculation instructions, formulas, force magnitudes, and/or other data. The force process can command distinct force sensations, such as vibrations, textures, jolts, or even simulated interactions between displayed objects. The host can send the local processor a spatial layout of objects in the graphical environment so that the microprocessor has a mapping of locations of graphical objects like enclosures and can determine interactions with the cursor locally. Such operation of local microprocessor in force feedback applications is described in greater detail in patent nos. 5,734,373 and 5,825,308. In an alternate embodiment, no local microprocessor 90 is included in interface device 31, and host computer 18 directly controls and processes all signals to and from the interface device 31.

A local clock 92 can be coupled to the microprocessor 90 to provide timing data, similar to system clock 78 of host computer 18 to, for example, compute forces to be output by actuators 106 and 112. In alternate embodiments using the USB communication interface, timing data for microprocessor 90 can be retrieved from the USB interface. Local memory 94, such as RAM and/or ROM, is preferably coupled to microprocessor 90 in interface device 31 to store instructions for microprocessor 90, temporary and other data, calibration parameters, adjustments to compensate for sensor variations can be included, and/or the state of the force feedback device.

Sensor interface 96 may optionally be included in device 31 to convert sensor signals to signals that can be interpreted by the microprocessor 90 and/or host computer system 18. For example, sensor interface 96 can receive signals from a digital sensor such as an encoder and convert the signals into a digital binary number. An analog to digital converter (ADC) can also be used. Such circuits, or equivalent circuits, are well known to those skilled in the art. Alternately, microprocessor 90 or host computer 18 can perform these interface functions. Actuator interface 98 can be optionally connected between the actuators 106 and 112 and microprocessor 90 to convert signals from microprocessor 90 into signals appropriate to drive the actuators. Interface 98 can include power amplifiers, switches, digital to analog controllers (DACs), and other components, as well known to those skilled in the art. In alternate embodiments, interface 98 circuitry can be provided within microprocessor 90 or in the actuators.

In a preferred embodiment, power is supplied to the actuators 106 and 112 and any other components (as required) by the USB. Alternatively, power from the USB can be stored and regulated by device 31 and thus used when needed to drive actuators 106 and 112. Or, a power supply can optionally be coupled to actuator interface 98 and/or actuators 106 and 112 to provide electrical power.

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A mechanical portion 100 is included in device 31 for the force feedback functionality of mouse 12. A suitable mechanical portion 100 is described in detail in co-pending PCT application WO 98/24183. A separate mechanical portion 102 is preferably provided for the force feedback functionality of wheel 16, as described in detail below with reference to Figures 5-8. In those embodiments not including force feedback in the planar mouse workspace (such as in Figure 1), the mechanical portion 100 need not be included. Furthermore, the embodiment of Figure 1 need not include a local microprocessor 90 or mechanical portion 100, where host computer 18 directly controls all forces on wheel 16.

Mechanical portion 100 preferably includes sensors 104, actuators 106, and mechanism 108. Sensors 104 sense the position, motion, and/or other characteristics of mouse 32 along one or more degrees of freedom and provide signals to microprocessor 90 including information representative of those characteristics. Typically, a sensor 104 is provided for each degree of freedom along which mouse 32 can be moved, or, a single compound sensor can be used for multiple degrees of freedom. For example, one sensor can be provided for each of two planar degrees of freedom of mouse 32. Examples of sensors suitable for embodiments described herein include optical encoders, analog sensors such as potentiometers, Hall effect magnetic sensors, optical sensors such as a lateral effect photo diodes, tachometers, and accelerometers. Furthermore, both absolute and relative sensors may be used.

Actuators 106 transmit forces to mouse 32 in one or more directions along one or more degrees of freedom in response to signals output by microprocessor 90 and/or host computer 18, i.e., they are "computer controlled." The actuators 106 produce "computer-modulated" forces which means that microprocessor 90, host computer 18, or other electronic device controls the application of the forces. Typically, an actuator 106 is provided for each degree of freedom along which forces are desired to be transmitted. Actuators 106 can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), voice coil actuators, etc. Passive actuators can also be used, including magnetic particle brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. In some embodiments, all or some of sensors 104 and actuators 106 can be included together as a sensor/actuator pair transducer.

Mechanism 108 is used to translate motion of mouse 32 to a form that can be read by sensors 104, and to transmit forces from actuators 106 to mouse 32. A preferred mechanism 108 is a closed-loop five-member linkage as described above in co-pending PCT application WO 98/24183. Other types of mechanisms can also be used, as disclosed in U.S. patent nos. 5,731,804; 5,767,839; 5,721,566; 5,805,140; and 5,691,898, all incorporated by reference herein. In the embodiment of Figure 1, mouse 12 typically has a ball and roller mechanism to sense the motion of the mouse. as is well known to those skilled in the art. User object 32 is preferably a

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mouse but can alternatively be a joystick, remote control, or other device or article, as described above.

Mechanical portion 102 interfaces the wheel 16 with the host computer 18. Portion 102 includes a sensor 110, an actuator 112, a mechanism 114, and wheel 16. Sensor 110 can be any suitable sensor for detecting the rotary motion of wheel 16, such as an optical encoder, potentiometer, or other varieties as described above for sensors 104. Alternatively, sensor 110 can be a linear sensor that senses linear motion of mechanism 114 converted from the rotary motion of wheel 16. Sensor 110 can be an absolute sensor, where absolute positions of the wheel in the range of motion are reported to host computer 18; or a relative sensor, in which changes in position from a previous position are reported to the host computer. Sensor 110 can be directly coupled to the user object 12 or 32, be coupled through a drive mechanism, or can be decoupled from the user object (e.g. by sensing motion using electromagnetic beam detectors and emitters).

Actuator 112 is any suitable actuator for providing rotary forces on wheel 16 and produces "computer-modulated" forces as referred to above similarly to actuators 106. In the preferred embodiment, actuator 112 is a DC current control motor that has a small enough size to fit into a small manipulandum such as a mouse and a small enough weight as to not interfere with mouse planar movement. Thus, the forces provided on wheel 16 may be small, but since the finger of a user is typically quite sensitive, small magnitude forces are sufficient to convey a variety of force sensations. In other embodiments, different types of active or passive actuators can be used as described above with reference to actuators 106. For example, passive actuators such as a magnetic particle brake, a friction brake, an electrorheological fluid actuator, or a magnetorheological fluid actuator, are quite suitable for use as actuator 112 due to their smaller size and weight and reduced power requirements. If such passive actuators are used, then a desired amount of play can be provided between actuator and wheel 16 to allow sensing of the wheel when the actuator is activated, as described in greater detail in patent nos. 5,721,566 and 5,767,839.

Also, a drive mechanism such as a capstan drive mechanism can be used to provide mechanical advantage to the forces output by actuator 112. Some examples of capstan drive mechanisms are described in patents 5,731,804 and 5,767,839. Alternatively, a belt drive system can be used as described below with reference to Figure 8.

In the described embodiment, the sensor 110 can input signals to a single sensor interface 96 used also for sensors 104 as described above. Actuator 112 can similarly use the actuator interface 98 also used by actuators 106. Alternatively, sensor 110 and/or actuator 112 can be provided with their own dedicated interfaces separate from interfaces 96 and 98.

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Mechanism 114 is provided to allows sensor 110 to sense the rotary motion of wheel 16 and to transmit rotary forces to the wheel 16 from actuator 112. Mechanism 114 can be a simple direct coupling of actuator 114 and sensor 112 to the wheel 16, as shown in Figures 5-6. Alternatively, a more complex mechanism can be used, such as a mechanism including a transmission system (e.g. a belt drive or capstan drive) as shown in Figures 7-8.

Other input devices 120 can be included in interface device 31 and send input signals to microprocessor 90 and/or host computer 18. Such input devices can include buttons, such as buttons 15 on mouse 12 or 32, used to supplement the input from the user to a GUI, game, simulation, etc. running on the host computer. Also, dials, switches, voice recognition hardware (e.g. a microphone, with software implemented by host 18), or other input mechanisms can be used. Furthermore, a safety or "deadman" switch can also be included to send a signal (or cease sending a signal) to microprocessor 90 and/or host 18 indicating that the user is not gripping the manipulandum 12 or 32, at which point the microprocessor 90 and/or host 18 commands the cessation of all output forces for safety purposes. Such safety switches are described in co-pending patent no. 5,691,898.

Furthermore, a safety switch 115 can be included for the wheel 16 to prevent forces from being output on the wheel when the user is not contacting or using it, and to prevent the wheel from spinning on its own when the user is not touching it. In one embodiment, the safety switch detects contact of a user's digit (finger, thumb, etc.) with the wheel. Such a switch can be implemented as a capacitive sensor or resistive sensor, the operation of which is well known to those skilled in the art. In a different embodiment, a switch or sensor that detects downward pressure on the wheel 16 can be used. For example, a switch can be sensitive to a predetermined amount of downward pressure, which will close the switch. A button switch for wheel 16 similar to that described below with reference to Figure 8, for example, can function as a safety switch. Or, a two-state switch can be used, where the first state is entered when a small amount of pressure is applied to wheel 16, functioning as the safety switch; and the second state is entered with a greater amount of pressure to activate a button switch and send a button signal. Alternatively, a pressure magnitude sensor can be used as the safety switch, where forces are output on the wheel only when a downward pressure magnitude over a minimum threshold is sensed. A pressure requirement for safety switch 115 has the advantage of ensuring good contact between finger and wheel before forces are output; output forces are enabled only when the user is moving or actively using the wheel. Thus, if the user simply rests his or her finger lightly on the wheel without intending to use it, no forces will be output to surprise the user.

FIGURE 5 is a perspective view of a first embodiment of the mechanical portion 102 for a force feedback wheel (e.g. mouse wheel or knob) including a direct drive mechanism. Sensor 110 and actuator 112 are grounded (schematically shown by ground 126), and mouse wheel 16 extends partially out of an aperture in the housing of mouse 12 or 32. Mouse wheel 16 is

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coupled to actuator 112 by a shaft 128; thus, when the actuator applies rotary force to shaft 128 about axis A, the user's finger 130 on wheel 16 will feel the rotary force about axis A. It should be noted that if the user is applying sufficient force in the opposite direction of the rotary force, the actuator operates in a stalled condition where the wheel 16 will not physically rotate, but the user will feel the rotational force.

Sensor 110 is coupled to the shaft 128 (or a portion of actuator 112 coupled to shaft 128) to measure the rotation of the shaft about axis A and thus the rotation of the wheel 16. Sensor 110 senses the rotation of wheel 16 even when no forces are applied to the wheel by actuator 112. In the embodiment of Figure 5, the actuator 112 is provided between the sensor 110 and the wheel 16. FIGURE 6 is a perspective view of a second embodiment 102' of mechanical portion 102, where the wheel 16 is positioned between the sensor 110 and actuator 112. Embodiment 102' is more appropriate than embodiment 102 when a desired play is introduced between actuator and wheel 16, since the sensor is desired to be rigidly coupled to wheel 16 without play in such an embodiment. In other respects, the embodiment 102' functions similarly to the mechanical portion 102.

FIGURE 7 is a perspective view of a third embodiment 102'' of mechanical portion 102 for force feedback mouse wheel 16. Wheel 16 is coupled to a pulley 132 by a rotatable shaft 134, where pulley 132, shaft 134, and wheel 16 rotate about axis B. In this embodiment, the pulley 132, shaft 134, and wheel 16 are preferably fixed at their rotation location, i.e., axis B is fixed with respect to mouse 12 or 32. Pulley 132 is coupled to a pulley 136 by a belt 138. Pulley 136 is rigidly coupled to a shaft 140, which is coupled to actuator 112 and to sensor 110, where pulley 136, actuator 112, and sensor 110 rotate about axis C. Mechanical portion 102'' thus operates similarly to the embodiment 102, except that the belt transmission system 142 that includes pulley 132, belt 138, and pulley 134 is used to scale the motion of wheel 16 and forces applied to wheel 16. For example, pulley 136 preferably has a smaller diameter than pulley 132 to allow the rotational motion of wheel 16 to be converted to a greater number of rotations of shaft 140, thus increasing the sensing resolution. Furthermore, a smaller rotation of shaft 140 translates to a greater amount of rotation of shaft 134, thus providing mechanical advantage to forces output by actuator 112 and allowing a smaller actuator to be used in mouse 12 or 32. In other embodiments, belt 138 can be a cable, or belt transmission system 142 can be a capstan drive system. Other mechanical transmission systems may also be used.

FIGURE 8 is a perspective view of a fourth embodiment 102''' of mechanical portion 102 for force feedback mouse wheel 16. Embodiment 102''' is similar to embodiment 102'' except that axis B is floating, i.e., may be rotated about axis C. Thus, the assembly including pulley 132, shaft 134, and wheel 16 may be rotated about axis C. This motion allows the wheel 16 to move approximately vertically with reference to the horizontal planar orientation of the

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mouse 12 or 32, as indicated by arrow 144. The wheel thus may be pushed down by the user into the housing of the mouse 12 or 32 like a button.

Spring contacts 146a and 146b are preferably provided in the path of the wheel 16. Contacts 146a and 146b each include a moving portion 148 that is forced toward a grounded portion 150 when the moving shaft 134 engages moving portions 148. A spring 152 is provided between each of the grounded and moving portions 150 and 148. When the moving portion 148 has been moved down enough to contact the grounded portion 150, a circuit is closed and a signal is sent to the microprocessor 90 and/or host computer 18 indicating that the wheel 16 has been pressed. The software running on the host computer can interpret the wheel-press signal to perform an associated task or process. When the user removes his or her finger from wheel 16, springs 152 force the moving portions 148 and the wheel 16 back to their original position. Other equivalent mechanisms may also be used in other embodiments to allow the wheel 16 to function as a button in addition to its rotational function. Furthermore, the contacts 146 can be used as a safety switch in some embodiments, as described above.

FIGURE 9 is a diagrammatic view of display screen 20 of host computer 18 displaying a graphical environment for use with the present invention. In the described example, a GUI 200 displays a window 202 on display screen 20. A cursor or pointer 204 is a user controlled graphical object that is moved in conjunction with the mouse 12 or 32 in its planar workspace.

The force feedback wheel 16 of the present invention can be used to control and/or enhance functions of the GUI 200. A normal mouse wheel can be used to scroll a document or view of the GUI, zoom a view, or pan a view by rotating the mouse wheel. In the present invention, several types of force sensations can be output on wheel 16 to enhance control or selection in the GUI of these types of rate-control functions. Any of the described force sensations can be combined on wheel 16 to provide multiple simultaneous force effects where appropriate.

One feature of the force feedback wheel is force detents. As described above with reference to Figure 3a, force detents are forces that attract the wheel to a particular rotational position and resist movement of the wheel away from that position, e.g. a "snap-to" detent. The detents can be programmable by an application developer or other designer/user to correspond with particular features of the GUI 200. For example, the host computer can send a high-level host command to the interface device 31 (e.g. microprocessor 90), where the host command has a command identifier and command parameters. The identifier (such as "WHEEL_DETENT") identifies the command as a force detent command, while the parameters characterize the detent forces. For example, parameters such as "θ angle of detent" and "magnitude" can be used, so that a command WHEEL_DETENT (θ, magnitude) characterizes a detent. A command of WHEEL_DETENT (20, 10) would command a wheel detent at an angle of 20 degrees on the

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wheel from a reference position (when viewing wheel coincident with axis of rotation), at a force magnitude of 10% of maximum force output (magnitude can also be expressed in other terms). Additional angle parameters can define additional detents located at different angles around the wheel in a range of 360 degrees, irregularly or regularly spaced as desired. Alternatively, "N pulses per revolution" can be a parameter to command N regularly-spaced force detents per revolution of the wheel. If a local microprocessor 90 is used, the microprocessor can implement the detents independently of control of the host based on the received host command.

For example, one standard GUI feature is a pull-down menu 206. Individual menu items 208 in the pull down menu 206 may be selected by the user using cursor 204. Once the pull-down menu has been displayed, the selection of a menu item 208 can be controlled by wheel 16 moving cursor 204 (and, optionally, vertical motion of mouse 12 or 32 can be disabled while the menu is displayed). For example, a menu item selection bar 209 (or highlighter) can be moved up or down menu 206 by rotating the wheel 16. The force detents can be output on wheel 16 to correspond with the spacing of menu items 208. Thus, the selection of a menu item is made easier from the use of detent forces, which substantially reduces the tendency of the user to overshoot a menu item when moving a cursor down the list of menu items. Furthermore, since the force detents are programmable, the user or software developer can set a rotational distance between detents to a particular preference, and can also set the magnitude of detent forces, e.g. for the "depth" of the detent which controls how easily the user may move the wheel past or out of a detent.

Detent forces can similarly be used for other GUI or application program features. For example, the spacing of objects on a document can be synchronized with force detents. As the document is scrolled using wheel 15, each time a particular object is scrolled past a predetermined location in a window, a force detent can be output. For example the spacing of lines 214 of text in a text document 212 can be synchronized with force detents so that if these text lines are scrolled by the cursor or other location in the window using the wheel 16, a force detent is output on the wheel 16. Similarly, the grid spacing on a spreadsheet or the links on a web page can be associated with force detents. The force detents can be spaced to correspond with the spacing of the text or other features to provide the user with greater feedback concerning the graphical features. Thus, a text document having single-spaced lines would cause force detents to be output in quick succession as the document is scrolled, while a text document having double-spaced lines would cause force detents to be output twice the rotational distance apart as the single spaced document. In other embodiments in which the wheel 16 is used to position the cursor 204 (described below), force detents can be output on wheel 16 when the cursor is moved over a particular graphical object, such as a text word, an icon, or a menu item 208. The flexibility of characterizing the computer-controlled actuator force detents makes

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these detents far more helpful to a user than the static mechanical detents provided in mouse wheels of the prior art.

A different force sensation which can be output on wheel 16 is a spring force or spring return force. Similarly to the knob 54 described with reference to Figure 3a, the spring return force resists rotational motion of the wheel away from a "rest position", where the magnitude of the spring force is proportional to the distance the wheel is rotated away from the rest position. This force can cause the wheel to spring back to its rest position when the user releases the wheel. A host command such as WHEEL_SPRING (state, stiffness) can be sent to the interface device 31 to characterize the spring return force, where the state ("ON" or "OFF") turns the spring force on or off and the stiffness indicates the magnitude of spring force output on the wheel. Also, additional parameters to characterize the spring can be included in the command, such as +k and –k (spring constant and direction), dB (deadband area around designated position in which no forces are applied), and +Sat, -Sat (saturation level over which the magnitude is not increased).

Such a spring force can be useful, for example, for isometric scrolling of a document or view in GUI 200. Isometric scrolling allows the user to exert pressure to control the direction and/or speed of scrolling or other rate control tasks. Isometric scrolling can be approximated through the use of a spring force, where the user exerts a force on the wheel 16 to rotate the wheel, but the spring force resists such a user force. The speed of scrolling is based on the distance of compression of the simulated spring. For example, the further the user pushes the wheel against the spring force, the faster a document will scroll. When the user releases the wheel, the actuators move the wheel back to its rest position (or the wheel is left in its current position) and the document stops scrolling. Alternatively, the user might wish to set preferences so that the document continues to scroll even when the wheel is released, where the activation of a different command or control stops the scrolling. In a different embodiment, the distance of a scrolling window or view can be based on the distance of compression of the simulated spring in a position control paradigm. For example, a document or a first-person view in a game can scroll based directly on the amount of rotation of the wheel against the spring force; when the user releases the wheel, the spring force moves both the wheel and the document or view back to the rest position. In a different embodiment, a spring return force can be used on wheel 16 when the wheel is used to control thrust or velocity of a simulated vehicle or character in a game. Or, the spring return force can be used in conjunction with zooming or panning functions in a GUI, game, or other graphical environment.

Another force sensation that can be used with wheel 16 is a jolt or pop force sensation. For example, a jolt can be command with a command such as WHEEL_JOLT(magnitude, duration), which characterizes the magnitude of the jolt force and its duration. Such jolts can be used to indicate to the user that designated objects have scrolled past a particular location on the

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screen. For example, each time a page break in a text document scrolls by the cursor 204 or scrolls past the bottom of the displayed window, a jolt can be output on wheel 16. Other objects such as web page links, images, etc. can also be associated with jolts. A jolt differs from a detent in that a jolt is time-based rather than spatially based; the jolt is output irrespective of the position of the wheel 16, and does not attract or repel the wheel from a particular rotational position.

A different force sensation that can be output on wheel 16 is a vibration. Like the jolt force, this type of force "effect" is time based, not based on the rotational position of the wheel. The vibration force can be commanded with a command such as WHEEL_VIBRATION (Frequency, Waveform, Magnitude) to characterize the vibration force, where "Waveform" can be a sine wave, square wave, triangle wave, or other-shaped wave. The vibration can be associated with particular graphical objects displayed on the screen, or be output based on events that occur in a host application. For example, a vibration can be output on wheel 16 when a warning or alert message is given, such as when the user receives new mail or when an error in a program occurs.

Other force sensations that can be output on wheel 16 are inertia, friction, and/or damping force. An inertia force is based on a simulated mass of an object, where the larger the mass, the greater the force resisting motion of the object. For example, a document can be assigned a simulated mass based on a characteristic of the document, such as the file size of the document, the font used in the document, etc. A document having a larger mass has a greater inertia force associated with it, so that the wheel 16 is more difficult to rotate when scrolling a large document as compared to scrolling a smaller document. The user can perceive the force on the wheel 16 and readily discern the size of the scrolled document. A friction force depends on a predefined coefficient of friction which causes a drag force on the user manipulandum. A damping force sensation is based on the velocity of an object, where the greater the velocity, the greater the damping force. This force feels like resistance to motion through a viscous liquid. The faster wheel 16 is rotated, the greater the damping force on the wheel. This can be used, for example, to provide areas of a document where scrolling is desired to be slower or controlled to a more fine degree, or to alert the user of a particular portion of the document as it scrolls by.

Another use for wheel 16 is for "coupled control." Coupled control refers to the position of cursor 204 on screen 20 being controlled both by the position of mouse 12 or 32 in its planar workspace as well as by the rotational position of wheel 16 about its axis. In one embodiment, the Y (vertical) screen coordinate of the cursor 204 is determined by the Y position of the mouse added to the Y position of the wheel 16, as summarized by the following:

$$Y_{CURSOR} = Y_{MOUSE} + Y_{WHEEL}$$

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Thus, the user can move the cursor 204 in a Y-direction on the screen by moving mouse 12 or 32 in a Y-direction in its workspace, and/or by rotating wheel 16 (where wheel 16 is preferably oriented in the Y-direction so that it rotates about an axis parallel to the plane of mouse movement and oriented in the X-direction). If the user wishes to move the cursor 204 only with the wheel 16, the mouse 12 or 32 can be kept stationary within its workspace; if the user wishes to move the cursor only with the mouse, the wheel is not moved. Furthermore, if a wheel is provided on mouse 12 or 32 for horizontal (X-direction) motion, the X position of the cursor 204 can be determined from both the X-direction of the mouse 12 or 32 in its workspace and by the rotational position of the X-oriented wheel. In other embodiments, the position control of cursor 204 by mouse 12 or 32 can be disabled at selected times to allow wheel 16 to have exclusive control of the cursor 204 position. For example, when a pull down menu 206 is selected by the user, the Y position of the mouse 12 or 32 can be ignored to allow the wheel 16 to exclusively control the Y position of the cursor 204 as the user is selecting a menu item 208 in the menu 206. One analogy to such dual mouse-wheel cursor control is a "reel metaphor", in which the wheel can be considered a reel of rigid string (or controlling the length of a telescoping pole), where the reel is positioned on the mouse 12 or 32 and the cursor 204 is attached to the end of the string (or pole). Assuming the string is fully wound on the reel (or pole is fully contracted), the mouse controls the position of the cursor directly. When the wheel is moved and the string unwound (or pole is expanded), the cursor has additional movement beyond the motion controlled by the mouse. The user can push or pull on graphical objects by winding or unwinding the reel, and feel the appropriate forces from such actions through the wheel 16.

When force feedback wheel 16 is used to control the position of cursor 204, force sensations can provide enhanced control and tactile information to the user. For example, when the user moves the cursor 204 against a graphical object designated as a wall or other obstruction using wheel 16, a wall force can be output on the wheel 16 to resist further motion of the wheel and cursor into the wall. One way to implement such a wall is to output a spring force on the wheel, calculated as $F_Y = K\Delta Y_{CURSOR}$, where K is a spring constant and ΔY_{CURSOR} is the distance of penetration of the cursor into the wall surface along the Y axis resulting from the sum of both wheel Y motion and mouse Y motion. To make the wall seem like it is impassable, the cursor is preferably continued to be displayed against the wall surface even as the wheel 16 is rotated to penetrate the wall spring force, providing a breaking of the mapping between cursor and physical manipulandum in a position control paradigm.

Other force sensations can also be output on wheel 16 when the wheel controls the position of the cursor. For example, a texture force can be output on the wheel when the cursor is moved over a textured region or object. Examples of textures include a bumpy surface and a slick icy surface. Alternatively, spring forces, damping forces, inertia forces, frictional forces, barrier forces, ramping effect forces, or dynamic effects can all be output on the wheel 16 and

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associated with the motion of the cursor and/or the interaction of the cursor with other graphical objects in GUI 200. Also, one or more of these forces can be combined with one or more other forces to create compound force sensations on wheel 16.

Furthermore, force profiles may be used to control the forces on wheel 16. Force profiles are sequences of individual force magnitudes that have been stored in a storage device such as local memory 92, host RAM 74, a hard disk drive, floppy disk, CD-R or CD Rewritable, DVD, or other storage device. The force magnitudes can be output by microprocessor 90 to the actuator 112 in sequence to apply a particular force sensation characterized by the force profile. The microprocessor can output the force profile magnitudes (or a subset thereof) at different rates or with different offsets from the stored magnitudes as commanded by host computer 18 and/or as a function of characteristics, such as wheel velocity/acceleration/current position, time, etc.

The force feedback functionality of wheel 16 described above can also be provided in different modes of the interface device 12 or 31, where the user, microprocessor 90, and/or host computer 18 can control which mode is currently active. Examples of two preferred modes are isotonic mode and isometric mode. Example of similar isometric and isotonic modes for mouse 12 or 32 are also described in U.S. Patent No. 5,825,308.

Isotonic mode is a position control mode for wheel 16, where the forces output on the wheel are synchronized or associated with the position of the wheel, and where the position of the wheel, when changed, incrementally changes the position or state of a graphical object provided by the host computer. For example, when a position control scrolling is provided by wheel 16, a document is scrolled by an amount corresponding to the amount the wheel is rotated. Similarly, the coupled control described above is a position control function, since a cursor is incrementally moved based on incremental rotations of the wheel 16.

Force sensations that are appropriate for such a position control wheel mode include force detents. For example, as explained above, force detents are output on the wheel depending on when text lines or spread sheet cells are scrolled by, where each detent is incrementally output as a document is scrolled, zoomed, panned, etc. Damping, friction, and inertia forces are also position control mode forces, where the force depends on the velocity (which is position based) or the position of the wheel and the cursor, document, or other object which is directly controlled by the wheel. Obstruction forces which represent hard stops to the wheel can be used in position control mode to represent the end of travel of the wheel; for example, when the end of a document is reached during a scrolling function, a hard stop force can be output to indicate this condition and resist further scrolling. Alternatively, a wall obstruction force on wheel 16 indicates that a wheel-controlled cursor has hit a wall. Texture forces are also appropriate in the position control mode, where the texture force is dependent on the position of the wheel; for

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example, in the coupled control embodiment where the wheel influences the position of the cursor, texture bump forces corresponding to bumps on the screen can be output on the wheel as the cursor moves over the bumps.

Isometric mode (or "pressure" mode) is a rate control mode for wheel 16. The distance of the wheel from a particular position controls a rate of a computer function, such as the rate of scrolling, zooming or panning, the rate of fast-forwarding/rewinding a computer-displayed movie, the rate of travel of a simulated vehicle, the rate of change for frequencies to increase when selecting radio stations, etc. An appropriate force sensation to use for such an isometric mode is the spring return force, which biases the wheel to center itself back at a starting or center position. The user feels the spring force get stronger the more the wheel is rotated from the center position, and this accordingly controls the rate of the computer function, e.g. the speed of scrolling. Detent forces can also be used in isometric mode, e.g. in conjunction with a spring return force. For example, the detents do not indicate an increment of wheel motion, but indicate the rate settings, making their selection easier for the user. Thus, a user might program three favored speed settings for the wheel in isometric mode, where the settings are indicated as force detents when the wheel is rotated to those speed settings, thereby assisting the user in finding and maintaining the wheel at those settings. In addition, jolt, vibration, or other time based forces can also be output on wheel 16 in an isometric mode, for example, to indicate events such as a page break scrolling by or the status of a simulated engine in a controlled simulated vehicle upon reaching a certain velocity.

The isotonic and/or isometric modes can be selected in a variety of ways. For example, when a button 15 is held down by the user, an isometric mode can be entered at the current location of the cursor or current displayed region of a document. When the button is released, isotonic mode can be entered. Alternatively, isometric mode can be activated when the cursor moves against an "isometric surface", as described below. Other modes can also be selected using buttons 15 or other input devices. For example, when a "cursor mode" of wheel 16 is selected, the wheel 16 can control cursor movement as explained above. When the cursor mode is inactive, the wheel 16 can control scrolling, zooming, or panning of a document/view, or other functions. Force feedback output on the wheel 16 is appropriate to the currently-selected mode. The modes can be selected by host computer 18, microprocessor 90, or the user in other ways in other embodiments.

Other modes can also be implemented for wheel 16. One type of mode is a "force functionality mode." For example, a thumb button (not shown) or other button 15 can toggle the force functionality mode in which designated graphical objects or regions displayed on screen 20 have other functions enabled by force feedback. A graphical object, such as a window or icon in a GUI, can act differently for selection of functions of the host computer or program, and/or for the forces associated with the object/region, depending on whether the force functionality mode

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is active. For example, when the mode is not active, the cursor can be moved normally through the border or edge of a window, with no force sensations associated with the movement over the window. However, when the force mode is active (such as by pressing or holding a particular button 15), a spring force will be output on mouse 32 and/or on wheel 16 opposing the movement of the cursor through the window border, i.e. the window border becomes an "isometric surface." This force is used as for "pressure scrolling" or as a "scroll surface", where the amount of penetration of the mouse against the spring force controls the speed of scrolling, zooming, etc. of a document displayed in that window (similar to isometric mode described above). In a "pressure clicking" or "click surface" embodiment, if the cursor is moved against the border of an icon or other object and the force functionality mode is active, a force will be output resisting motion of the cursor into the icon; when the mouse 32 and/or wheel 16 moves against the force a threshold distance, the icon is selected as if the cursor had clicked or double-clicked on the icon. These types of features are especially applicable to wheel 16 when in the coupled cursor control embodiment described above. In other embodiments, other input devices besides or in addition to buttons 15 can control the force functionality mode. Or, different input devices can control different modes.

FIGURE 10 illustrates an application for a control knob embodiment of the present invention. A control panel 212 is provided for a device 210 and includes a control knob of the present invention. In the described embodiment, device 210 is an audio device that controls the output of sound, such as music or speech, from speakers that are connected to the device 210. For example, a common embodiment of device 210 is a stereo system that includes the ability to play sound from one or more media or signals, such as cassette tapes, digital audio transmission (DAT) tapes, compact discs (CD's) or other optical discs, or radio signals transmitted through the air from a broadcasting station.

The device 210 can also include additional or other functionality not related to audio control and output. For example, many vehicles include electronic systems to control the temperature in the vehicle cabin (air conditioning, heat, etc.), as well as systems to provide information on the current operating characteristics of the vehicle, such as current speed, engine temperature, fuel or other fluid levels, whether windows of the vehicle are open, etc. Other systems may include a navigation system that displays a map and the current location of the vehicle with respect to the map, a cellular telephone or other portable telephone control system, and a security/alarm system. Device 210 can include the ability to display information from and/or influence such other systems in a vehicle or other environment, such as a house, office, etc.

Alternatively, device 210 can be a variety of other electronic or computer devices. For example, device 210 can be a home appliance such as a television set, a microwave oven or other kitchen appliances, a washer or dryer, a home stereo component or system, a home computer, a

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set top box for a television, a video game console, a remote control for any device, a controller or interface device for a personal computer or console games, a home automation system (to control such devices as lights, garage doors, locks, appliances, etc.), a telephone, photocopier, control device for remotely-controlled devices such as model vehicles, toys, a video or film editing or playback system, etc. Device 210 can be physically coupled to the control panel 212, or the panel 212 can be physically remote from the device 210 and communicate with the device using signals transferred through wires, cables, wireless transmitter/receiver, etc.

Device 210 preferably includes a front panel 212, a display 214, several control buttons 216, and one or more control knobs 218 of the present invention. Front panel 212 can be mounted, for example, on the interior of a vehicle, such as on or below the dashboard, or in some other convenient area. Alternatively, the front panel 212 can be the surface of the external housing of the device 210 itself, such as a stereo unit. The device 210 may include several functions, such as playing an audio track, adjusting volume, tone, or balance of an audio output, displaying an image (icons, a map, etc.), or adjusting the temperature or fan speed in a vehicle, which can be changed or set by the user manipulating the controls of the device 210 on front panel 212.

Display 214 is provided to show information to the user regarding the controlled device or system and/or other systems connected to the device 210. For example, options 220 can be displayed to indicate which function of the device 210 is currently selected. Such options can include "radio," "tape," "CD,", or power, as shown. Other information, such as the current radio frequency 222 selected for a radio tuner, can also be displayed. Furthermore, any information related to additional functionality of the device 210 can also be displayed. For example, information 224 can be provided to allow the user to select one or more functions not related to the audio operation of the device 210. In some embodiments, a map or similar graphical display can be shown on display 214 of an device 10 to allow the user to navigate. Some examples of functions displayed by a display 214 are shown with respect to Fig. 2, below. In other embodiments, display 214 can be a separate monitor displaying a graphical user interface or other graphical environment as controlled by a host computer. Display 214 can be any suitable display device, such as an LED display, LCD display, gas plasma display, CRT, or other device. In some embodiments, display 214 can include a touch-sensitive surface to allow a user to touch displayed images directly on the display 214 to select those images and an associated setting or function.

Control buttons 216 are often provided on device 210 to allow the user to select different functions or settings of the device. For example, on an audio device, buttons 216 can include radio station preset buttons, rewind/fast forward tape functions, power, speaker loudness, etc. Virtually any function of the device can be assigned to buttons 216. The buttons 216 may also be used in conjunction with the control knobs 218, as described below.

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Control knobs 218 are provided to allow the user a different type of control of functions and settings of device 210 than the buttons 216 allow. Knobs 218, in the described embodiment, are approximately cylindrical objects engageable by the user. The knobs 218 can alternatively be implemented as a variety of different objects, including conical shapes, spherical shapes, dials, cubical shapes, rods, etc., and may have a variety of different textures on their circumferential surfaces, including bumps, lines, or other grips, or even projections or members extending from the circumferential surface. In addition, any of variety of differently-sized knobs can be provided; for example, if high-magnitude forces are output, a larger-diameter cylindrical knob is often easier for a user to interface with device 210. In the described embodiment, each knob 218 rotates in a single rotary degree of freedom about an axis extending out of the knob, such as axis A. The user preferably grips or contacts the circumferential surface 226 of the knob 218 and rotates it a desired amount. Force feedback can be provided in this rotary degree of freedom in some embodiments, as described in greater detail with reference to Figs. 12a and 12b.

Furthermore, the control knobs 218 of the present invention allow additional control functionality for the user. The knobs 218 are preferably able to be moved by the user in one or more directions approximately perpendicular to the axis A of rotation, e.g. parallel to the surface of the front panel 212 as shown in Fig. 10 ("transverse motion" or "transverse direction"). This transverse motion is indicated by arrows 228. For example, the knob 218 can be moved in the four orthogonal directions shown, or may be moveable in less or more directions in other embodiments, e.g. only two of the directions shown, or in eight directions spaced at 45 degree intervals about axis A. In one embodiment, each transverse direction of the knob is spring loaded such that, after being moved in a direction 228 and once the user releases or stops exerting sufficient force on the knob, the knob will move back to its centered rest position. In other embodiments, the knob can be provided without such a spring bias so that the knob 218 stays in any position to which it is moved until the user actively moves it to a new position.

This transverse motion of knob 218 can allow the user to select additional settings or functions of the device 210. In some embodiments, the additional control options provided by knob 218 allow the number of buttons 216 and other controls to be reduced, since the functions normally assigned to these buttons can be assigned to the knob 218. For example, the user can move a cursor 30 or other visual indicator on display 214 (e.g. pointer, selection box, arrow, or highlighting of selected text/image) to a desired selection on the display. Thus, the cursor 230 can be moved from the "radio" selection shown to the "tape" selection by moving the knob 218 in the down direction as shown in Fig. 10. Or, the cursor 230 can be moved to the "CD" selection by moving the knob 218 in the direction to the right. If knob 218 is provided with diagonal directions (e.g. at 45 degree intervals), the user can move the cursor 230 from the "radio" selection directly to the "off" selection. The user can similarly move cursor 230 or a

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different indicator to the other information settings 224, to the frequency display 222, or to any other displayed option, setting, or area/region on the display 214.

Besides such a cursor positioning mode, the transverse motion of knob 218 can also directly control values or magnitudes of settings. For example, the left motion of knob 218 can decrease the radio station frequency value 222, where the value can decrease at a predetermined rate if the user continually holds the knob 218 in the left direction. The right motion of the knob 218 can similarly increase the frequency value 222. In another example, once one of the information settings 24 is selected, a sub menu can be displayed and the directions 228 of knob 218 can adjust air temperature, a timer, a cursor on a displayed map, etc.

Different modes can also be implemented; for example, the default mode allows the user to control cursor 230 using the directions 228 of the knob. Once the cursor is located at a desired setting, such as the frequency value 222, the user can switch the mode to allow the directions 28 to control the setting itself, such as adjusting the value 222. To switch modes, any suitable control can be used. For example, the user can push a button, such as button 229, to toggle a mode. Alternatively, the user can push or pull the knob 218 to select the mode; this functionality of the present invention is described below. Or, some or all of the directions 228 can be used to select modes; for example, the down direction might switch to "volume" mode to allow the user to rotate the knob to adjust volume; the up direction can switch to "adjust radio frequency" mode, and the left direction can switch to "balance" mode (for adjusting the speaker stereo balance for audio output with rotation of knob 218).

In addition, the control knobs 218 are preferably able to be pushed and/or pulled in a degree of freedom along axis A (or approximately parallel to axis A). This provides the user with additional ways to select functions or settings without having to remove his or her grip from the knob. For example, in one preferred embodiment, the user can move cursor 230 or other indicator on the display 214 using the directions 228 of the knob 218; when the cursor has been moved to a desired setting or area on the display, the user can push the knob 218 to select the desired setting, much like a mouse button selects an icon in a graphical user interface of a computer. Or, the push or pull function can be useful to control the modes discussed above, since the user can simply push the knob and rotate or move the knob while it is in the pushed mode, then release or move back the knob to select the other mode. The modes discussed above can also be toggled by pushing or pulling the knob 218. The push and/or pull functionality of the knob 218 can be provided with a spring return bias, so that the knob returns to its rest position after the user releases the knob. Alternatively, the knob can be implemented to remain at a pushed or pulled position until the user actively moves the knob to a new position.

A slider control 232 of the present invention may also be included in device 210. Slider control 232 includes a slider knob 234 which is grasped by the user and moved in a linear

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direction as shown by arrow 236. In the present invention, slider control 232 preferably includes force feedback functionality. Thus, as the user moves the knob 234, force sensations such as a spring force, a damping force, jolts, detents, textures, or other forces can be output and felt by the user. Furthermore, the slider knob 234 can include a button 238 which can be pressed by the user similarly to the push knob embodiment discussed above with reference to knob 218. Alternatively, the knob 234 can be pushed and/or pulled similarly to the knob 218 as described above. Slider control 232 can control any of the various functions, settings, or options of the device 210. For example, the motion left or right of knob 234 can control the radio frequency 222, where force detents are output for each station and/or each preset station previously programmed by the user. Or, the cursor 230 can be moved using the slider knob 234, such that when the cursor reaches a desired setting or selection, the user can push button 238 or push on the knob 234 to select that setting. Other functions such as volume, balance, tone, map functions, temperature functions, or mode selection can also be controlled by the slider control 232. Slider control is described in greater detail with respect to Figure 14.

FIGURE 11 is an example showing images which can be displayed on display 214 to assist the user in selecting options with knobs 218 and/or slider control 232. Display 214 can present icons as shown, in this example for the control of audio output signals from device 210. Icon 246 is selected to control the volume of the audio output using knob 218, where the circular pointer 242 can be moved in accordance with the knob 218. Icon 247 is used to control the frequency of the radio tuner (the current selected frequency can be displayed as well), and the icons 248, 249, and 251 are used to control the balance, treble, and bass of the audio, respectively. For example, the indicator 244 can be moved left or right depending on the current setting. Cursor 245 is used to select one of the icons to allow the control of the functions associated with the selected icon. Cursor 245 indicates which of the icons in display 214 are currently selected. The icon can be moved from each icon to the next by rotating the knob 218. Alternatively, the transverse motion of the knob can move the cursor 245. A function of the device designed by the selected icon can be selected by pushing the knob 218 in the linear direction. The cursor can be a square or other-shaped box, or the currently-selected icon can be highlighted to indicate the cursor's location.

It should be noted that each of the icons can preferably be set to a position control mode or to a rate control mode as desired by the user. For example, the user may select position control for volume 246 and rate control for the functions of icons 247, 248, 249, and 251, or any other combination. In position control mode, force detents are preferably output to indicate particular settings or how far the knob 218 has been rotated. In rate control mode, detents can also be output. For example, the user maintains the knob 218 at a rotary position away from the center position in opposition to a spring return force, and a detent force (e.g., jolt) is output to indicate how much a particular value has been changed. For example, a jolt can be output for

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each 10 MHz of frequency that is increased, or for each particular amount of treble or bass that has been adjusted.

Other icons can be displayed in other embodiments. For example, an for vent location can be selected using cursor 245 to determine which vents in the car provide air flow, where a top vent, a bottom vent, or both top and bottom vents can be selected. A fan speed icon can be selected to choose a fan speed setting for the air flow from the vents in the car. In a preferred force feedback implementation, once the fan speed icon has been selected by pushing in the knob 218, the user may rotate the knob 218 to select the fan rotation speed in a position control mode. A small vibration can be output on the knob 218 in the rotary degree of freedom, where the frequency (or magnitude) of the vibration forces correlate with the magnitude of fan rotation speed, i.e., a high fan speed provides a fast vibration. Furthermore, detents are preferably output superimposed on the vibration forces so that the user can feel the fan settings at the detents. This allows the user to select fan speed based purely on tactile feel, so that the driver need not look at the display 214. A temperature icon can be selected to adjust the temperature in the car. The temperature can preferably be adjusted by rotating knob 218, where force detents indicate each temperature setting. Icons for moving mechanical components, such as seats or mirrors, can be provided, where a rate control force mode is used to control the position of the components.

FIGURE 12a is a perspective view and FIGURE 12b is a side elevational view of one implementation of control knob 218 of the present invention. In this implementation, knob 218 includes the ability to move transversely in four directions, and the knob 218 can also be pushed for additional selection ability.

Knob 218 is rigidly coupled to a rotatable shaft 250 which extends through the grounded front panel 212 (shown in dashed lines). Shaft 250 extends through a four-way switch 252 which detects the transverse motion of the knob 218 in directions 228. The knob 218 is biased toward the centered rest position within switch 252 by a spring member 264, described in greater detail below. When the shaft 250 is moved in any of the provided transverse directions, a corresponding micro switch (not shown) included on the interior sidewall of the four-way switch 52 is closed, thus causing a signal to be output on leads 254. Thus, switch 252 preferably includes individual micro switches, one for each provided transverse direction (four individual switches in the described embodiment). A suitable switch for use as switch 252 is a "hat switch" which is commonly provided for analog joystick controllers for personal computers and allows 4 or 8 directions to a moveable member. For example, joystick hat switches manufactured by such companies as CH Products, Inc. or Logitech can be used. In other embodiments, two-way, eight-way, or other types of switches can be used, depending on how many directions are desired.

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A pusher member 256 is rigidly coupled to shaft 250 next to the switch 252. Since the switch 252 includes an aperture through which the shaft 250 extends, the knob 218, shaft 250 and pusher member 256 are operative to move as a unit along axis A with respect to the front panel (ground) and the switch 252. A switch 258 (see Fig. 12b) is coupled to a grounded member 260 and is provided in the path of the pusher member 256. Thus, when the knob 218 is pushed by the user, the shaft 250 and the pusher member 256 are moved along axis A in a direction indicated by arrow 262 (see Fig. 12b). This causes pusher member 256 to engage the button 264 of the switch 258, causing the button 264 to be pushed inward and close (or open) the switch. The pushing motion of the knob 218 is thus sensed.

In other embodiments, a sensor can be provided to sense a range of positions of the knob 218 or a continuous motion of the knob 218 linearly along axis A. For example, a Hall effect switch can be provided on pusher member 256 which measures the position of the pusher member 256 relative to a grounded magnet on member 260 (or the Hall effect switch can be placed on the member 260 and the magnet can be placed on the member 256). Or, an optical sensor (such as a photodiode) or other type of sensor can detect the position of the member 256 and/or knob 218. In such an embodiment, the position of the knob along axis A can proportionately control a function or setting of the device 210. For example, such movement can control the volume of audio output of the device, motion of a cursor across a display, or the brightness of lights inside a vehicle.

A pull switch can be implemented similarly to the push switch shown in Figs. 12a and 12b. For example, a switch similar to switch 258 can be grounded and provided on the opposite side of pushed member 256 so that when knob 218 is pulled in a direction opposited to direction 262, a button on this switch is engaged by the pusher member to detect the pulled motion. The pull motion of knob 218 can also be sensed in a continuous range similar to the push embodiments described above. In some embodiments, both push and pull motions of the knob 218 may be provided and sensed.

A spring member 264 is rigidly coupled to the pushing member 256 at one end and is rigidly coupled to a rotatable end member 266 at its other end. Spring member 264 is compressed when the knob 218 and pusher member 256 are moved in the direction of arrow 262. Spring member 264 thus provides a spring force that biases the knob 218 in the direction opposite to direction 262. If the knob 218 is not forced in direction 262, the spring bias moves the knob 218 opposite to direction 262 until the knob reaches its rest position. In those embodiments including a pull motion of the knob 218 in the direction opposite to direction 262, a spring member can be included on the opposite side of pusher member 256 to spring member 264, to bias the knob 218 in direction 262 after the user has pulled the knob. In yet other embodiments, no spring member 264 is provided, and the knob 218 remains at any pushed or pulled position until actively moved to a new position by the user.

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Spring member 264 also provides the transverse motion of knob 218 in the directions 228. The flexure of the spring element allows the knob to move in transverse degrees of freedom, while still being relatively torsionally stiff to allow forces to be transmitted effectively from an actuator to the knob 218 about axis A. In other embodiments, other types of couplings can be provided to allow a pivot or translational motion in the directions 228. For example, flexible disc servo couplings or one-piece flexible shaft disc couplings can be provided; such couplings are available from Renbrandt, Inc. of Boston, MA and Helical Products Company , Inc. of Santa Maria, CA. In other embodiments, bent space frames provided in a square-plate coupling or a rectangular coupling can be used. Furthermore, a different alternate flexible coupling embodiment is described in greater detail with respect to Figs. 4a-4c.

End member 266 is coupled to a rotatable shaft 268 of an actuator 270. The housing 272 of actuator 270 is rigidly coupled to grounded member 274, and the shaft 268 rotates with respect to the housing 272 and the member 274. Actuator 272 can be controlled to output force on rotating shaft 68 about axis A, thus driving the shaft and all components rigidly coupled to the shaft about axis A. The shaft 268 thus rotates end member 266, spring member 264, pusher member 256, shaft 250, and knob 218. The output force on knob 218 is felt by the user as force feedback. Actuator 270 can be any of a variety of different types of actuators, including a DC motor, voice coil, pneumatic or hydraulic actuator, magnetic particle brake, etc. A sensor 276 has a shaft rigidly coupled to the rotating shaft 268 of the actuator 270 and thus detects the rotation of the shaft 268 and the knob 218 about axis A. Sensor 276 is preferably a digital optical encoder but can alternatively be a different type of sensor, such as an analog potentiometer, a photodiode sensor, a Hall effect sensor, etc.

The force feedback output on knob 218 can include a variety of different force sensations. The force feedback can be integrally implemented with the control functions performed by the knob. A basic force sensation is force detents that are output at particular rotational positions of the knob to inform the user how much the knob has rotated and/or to designate a particular position of the knob. The force detents can be simple jolts or bump forces to indicate the detent's position, or the detents can include forces that attract the knob to the particular rotational detent position and resist movement of the knob away from that position. The position can correspond to a particular radio station frequency or other station (e.g., television station frequency), thus making selection easier for the user. Such detents can be provided for additional functions, such as volume control for sound speakers, fast forward or rewind of a video cassette recorder or computer-displayed movie (such as a DVD movie), scrolling a displayed document or web page, etc. Force feedback "snap-to" detents can also be provided, for example, for the favorite station frequencies preprogrammed by the user, where a small force biases the knob to the detent position when it is just outside the position.

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Also, the magnitude of the force detents can differ based on the value being controlled. For example, a radio frequency having a higher value might be associated with a stronger force detent, while a lower radio frequency might be associated with a weaker force detent when it is displayed, thus informing the user generally of the radio station being displayed without requiring the user to look at the display 214 (which is particularly useful when operating the device 210 while performing another task, such as driving a vehicle). In some embodiments, the user can also change the magnitude of detents associated with particular values, such as radio stations, to preferred values so as to "mark" favorite settings. Programmability of the location of the detents in the rotary degree of freedom is also convenient since preferred radio frequencies are most likely spaced at irregular intervals in the radio frequency range, and the ability to program the detents at any location in the range allows the user to set detents to those preferred stations. In addition, the knob can be moved by the actuator 270 to select the nearest preprogrammed station or preferred setting. Also, different sets of detent force profiles can be stored in a memory device on the device 230 and a particular set can be provided on the knob 218 by a microprocessor or other controller in the device 230.

Another type of force sensation that can be output on knob 218 is a spring force. The spring force can provide resistance to rotational movement of the knob in either direction to simulate a physical spring on the knob. This can be used, for example, to "snap back" the knob to its rest or center position after the user lets go of the knob, e.g. once the knob is rotated past a particular position, a function is selected, and the user releases the knob to let the knob move back to its original position. A damping force sensation can also be provided on knob 218 to slow down the rotation of the knob, allowing more accurate control by the user. Furthermore, any of these force sensations can be combined together for a single knob 218 to provide multiple simultaneous force effects.

The spring return force provided in the rotary degree of freedom of the knob 218 can also be used to implement a rate control paradigm. "Rate control" is the control of a rate of a function, object, or setting based on the displacement of the knob 218 from a designated origin position. The further the knob is moved away from the origin position, the greater the rate of change of controlled input. For example, if a rate control knob 218 with a spring return force is used to control the radio frequency, then the further the knob is moved from the center origin position, the faster the radio frequency will change in the appropriate direction. The frequency stops changing when the knob is returned to the origin position. The spring force is provided so that the further the user moves the knob away from the origin position, the greater the force on the knob in the direction toward the origin position. This feels to the user as if he or she is inputting pressure or force against the spring rather than rotation or displacement, where the magnitude of pressure dictates the magnitude of the rate. However, the amount of rotation of the

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knob is actually measured and corresponds to the pressure the user is applying against the spring force. The displacement is thus used as an indication of input force.

This rate control paradigm differs from the standard knob control paradigm, which is known as "position control", i.e. where the input is directly correlated to the position of the knob in the rotary degree of freedom. For example, in the radio frequency example, if the user moves the knob to a particular position, the radio frequency is changed to a particular value corresponding to the rotary position of the knob. Force detents are more appropriate for such a paradigm. In contrast, in the rate control example, moving the knob to a particular position causes the radio frequency to continue changing at a rate designated by the position of the knob.

Since the spring force and detent forces are programmable and can be output as directed by a microprocessor or other controller, a single knob 218 can provide both rate control and position control over functions or graphical objects. For example, a mode selector, such as a button or the push/pull knob motion, can select whether rate control or position control is used. One example of a force feedback device providing both rate control (isometric input) and position control (isotonic input) is described in greater detail in U.S. Patent No. 5,825,308, incorporated herein by reference. Such rate control and position control can be provided in the rotary degree of freedom of the knob 218. Also, if knob 218 is provided with force feedback in the transverse degrees of freedom or in the push/pull linear degree of freedom, then the rate control and position control modes can be provided in those degrees of freedom.

Other force sensations that can be output on knob 218 include forces that simulate ends of travel for the knob 218 or inform the user that the end of travel has been reached. For example, as the user rotates the knob in one direction to adjust the radio frequency 222, the end of the radio frequency range is reached. There is no hard stop on the knob 218 at this position, but the actuator 270 can be controlled to output an obstruction force to prevent or hinder the user from rotating the knob further in that direction. Alternatively, a jolt force can be output that is stronger in magnitude than normal detents, which informs the user that the end of the frequency range has been reached. The user can then continue to rotate the knob in that direction, where the displayed frequency 222 wraps around to the beginning value in the range.

In another alternate embodiment, one or more of the transverse motions of knob 218 in directions 228 can be actuated. For example, a greater range of motion can be provided for each transverse direction of the knob than typically allowed by a hat switch, and a linear or rotary actuator can be provided to output forces in the transverse degree of freedom, in one or both directions (toward the center position and away from the center position of the knob). For example, one or more magnetic actuators or solenoids can be used to provide forces in these transverse directions.

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Furthermore, in other embodiments, the pull and/or push motion of knob 218 along axis A can be actuated. For example, a jolt force can be output on the knob in the linear degree of freedom along axis A as the user pushes the knob. Also, the spring return force provided by spring member 264 can instead be output using an actuator controlled by a microprocessor.

It should be noted that the embodiment of Figs. 12a and 12b is not the only embodiment of the present invention. For example, some embodiments may only include the transverse motion of knob 18 and not the push and/or pull functionality nor the force feedback functionality. Other embodiments may only include the push and/or pull functions. Yet other embodiments may only include force feedback with transverse knob motion, or force feedback with push and/or pull functions.

FIGURE 13a is a perspective view of an alternate embodiment 280 of the control knob 218 of the present invention. In embodiment 280, knob 218 is coupled to shaft 250, which is rigidly coupled to a flex member 282. Flex member 282 includes a base plate 284 and a plurality of bent portions 286 extending from the base plate 284. For example, as shown in FIGURE 13b, the flex member 282 can be formed by cutting out the circular base plate 284 and the portions 286 from a unitary piece 285 of material, such as spring steel or stainless steel. The unitary piece is preferably provided as a thin sheet. Holes 288 or other apertures can be placed near the ends of the portions 286. Referring back to Fig. 13a, the portions 286 are then bent such that the holes 288 substantially align with the other holes 288, where the holes 288 are aligned with axis B that extends approximately perpendicular to the surface of the base plate 284. The base plate 284 is rigidly coupled to the rotating shaft of the actuator 270.

FIGURE 13c is a side elevational view of the embodiment 280 of Fig. 13a. In the described embodiment, knob 218 is coupled to shaft 250, which extends through a switch 290 and is coupled to the bent portions 286 of the flex member 282. The switch 290 is preferably similar to the switch 252 described above with reference to Figs. 12a and 12b. For example, a microswitch can be provided on the inside surface of the housing of switch 290 for each transverse direction of knob 218 that is to be sensed. The base plate 284 of the flex member 282 is rigidly coupled to shaft 292 of actuator 270. The shaft 292 is rigidly coupled to a shaft (not shown) of sensor 276, which has a grounded housing that is coupled to the grounded housing of actuator 270.

Alternatively, a plurality of sensors can be positioned external to the flex member 282 instead of using switch 290. For example, switches 294 can be positioned on two or more sides around the flex member 282, depending on how many directions are to be sensed. Switches 294 can be contact switches that each detect when the portions 286 move to engage the contact switch, thus indicating movement of knob 218 in a particular transverse direction. Alternatively, members can be positioned on shaft 250 which extend to the sides of the shaft and which engage

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electrical contacts or other sensors. In other embodiments, other switches or sensors can be used, as described above in the embodiment of Fig. 12a. A spring (not shown) can also be coupled to the shaft 250, flex member 282, or knob 218 to provide linear motion along the axis B and allow the knob 218 to be pushed and/or pulled by the user, as described in the embodiment of Fig. 12a. Some types of flexible couplings that allow transverse motion of the knob 218 may also allow linear motion along axis B, such as flexible disc servo couplings, in which case such as spring may not be needed.

In operation, the transverse motion of knob 218 in embodiment 280 operates as follows. The knob 218 is moved by the user approximately in a transverse direction 228, which causes the shaft 250 to move with the knob by pivoting approximately about the end of the shaft 250 where it is coupled to the portions 286. Shaft 250 is allowed such movement due to the flexibility in portions 286. In some embodiments, the knob 218 is also allowed to translate in a transverse direction 228 as well as or in addition to pivoting approximately in directions 228. When the knob 218 is rotated about axis B (by the user or the actuator), the shaft 250 rotates about its lengthwise axis, causing the flex member 282 to rotate about axis B. Since the portions 286 are stiff in the rotational direction about axis B, torque output on the shaft 250 and on the flex member 282 is transmitted accurately from actuator 270 to knob 218 and from knob 18 to sensor 276. Thus, the rotation on flex member 292 causes the shaft 92 to rotate, which is sensed by sensor 276. The rotational force about axis B output by actuator 70 is similarly transmitted from shaft 292, through flex member 282, to shaft 250 and knob 218.

FIGURE 14 is a perspective view of an exemplary embodiment for the slider control 232 as shown in Fig. 10. Slider control 232 includes slider knob 234 which may move in a linear degree of freedom as indicated by arrow 236. In the described embodiment, a transmission member 300 is rigidly coupled to the knob 234 and extends through a slit or opening 302 in the front panel 212 or other grounded member. Transmission member 300 can be coupled to an actuator, such as linear voice coil actuator 304.

The member 300 can move in and out of a housing 301 of actuator 304 as indicated by arrow 303. The housing 301 preferably includes a central core 307 and a number of elongated magnets 309. An armature 305 includes a hollow, cylindrical member having an inner surface which slidingly engages the core 307. Wrapped around the armature 305 are coils 310 that are electrically coupled to actuator and/or sensor interfaces. The armature 305 is coupled to the transmission member 300 so that the armature 305 and member 300 can move in a linear fashion as indicated at arrow 303. Other voice coil configurations can also be used, such as differently shaped cores, different coil layouts, etc. Voice coil actuator 304 can serve both as a sensor and an actuator. Alternatively, the voice coil can be used only as an actuator, and a separate sensor 306 can be used. Separate sensor 306 can be a linear sensor that senses the motion or position of an extension 312 that is coupled to the transmission member 300 and moves linearly when the

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transmission member moves. Voice coil actuators such as actuator 304 are described in greater detail in U.S. Patent No. 5,805,140, the disclosure of which is incorporated herein by reference. In particular, the operation of the voice coils as actuators and/or sensors is described therein.

Other types of actuators 304 and transmissions can also be used in slider control 232. For example, a capstan drive and cable transmission can provide linear forces on the knob 234. Other types of actuators suitable for use with the slider include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer, etc. Passive actuators may also be used, such as magnetic particle brakes, friction brakes, fluid controlled passive actuators, or other actuators which generate a damping resistance or friction in a degree of motion.

Slider knob 234 can also include a button 238 which is used to provide input to the device 210. In yet other embodiments, the slider knob 234 can be pushed and/or pulled in a linear degree of freedom approximately perpendicularly to the surface of front panel 212. In such an embodiment, a moveable contact switch can be provided between the knob 234 and the transmission member 300. A spring member can also be provided similarly to the embodiment of Figs. 12a-12b and 13a-13c to bias the knob 234 to a neutral rest position.

The force sensations and modes described above for the rotary knob in Figs. 12a-12b and 13a-13c may also be used for the slider control 232 in a linear degree of freedom. For example, force detents can be applied in a position control paradigm as the knob 234 is moved in its linear degree of freedom. In a rate control paradigm, a spring return force can bias the knob 234 toward a center origin position, for example the center of the range of motion of the knob. The further the user moves the knob from the origin position, the greater the spring force opposing that motion and the greater the rate of the controlled value changes (increases or decreases). Other force effects include damping forces, texture forces, jolts, obstruction forces, assistive forces, periodic forces such as vibration forces, and end-of-travel forces.

FIGURES 15a and 15b are diagrammatic illustrations illustrating detent force profiles suitable for use with the knobs of device 210. Detent force profiles can be implemented by a microprocessor or other controller based on instructions stored in a computer readable medium, such as a memory circuit, magnetic disk, optical disk, etc. In Fig. 15a, a detent force profile is shown. The vertical axis F represents the magnitude of force output, where a positive F value indicates force in one direction, and a negative F value indicates force in the opposite direction. The horizontal axis d represents the distance or position of the moved user object (knob) in a degree of freedom, where the origin position O indicates the position of the detent, a positive d is a position past the origin of the detent in one direction, and a negative d is a position past the origin of the detent in the opposite direction. The curve 324 represents the force output for a single detent over a position range for the detent. Thus, for example, if the user moves the knob

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clockwise toward the detent origin O1, the motion may be from the left toward the origin O1 on the axis d. A force toward the origin is output at position P1 at a magnitude -M to assist the user in moving the knob clockwise toward the origin. As the user continues to move the knob clockwise toward the origin O1, the assisting force is decreased in magnitude until no force is output when the knob is positioned at the origin position. If the user moves the knob counterclockwise from the origin position O1 (from right to left), the force will resist such motion in an increasing manner until the knob has been moved to position P1, after which the force magnitude drops to zero. Similarly, on the positive side of the d axis, if the user rotates the knob clockwise away from the detent origin position O1 (corresponding to movement from left to right), an increasing magnitude of force is output until the knob reaches the position P2, at which point the force magnitude drops from its maximum at M to zero. If the user moves the knob counterclockwise from position P2 toward the origin O1, the user initially feels a large magnitude force assisting that movement, after which the assisting force gradually decreases until it is zero at the origin O1. Preferably, point P1 is at an equal distance from origin O1 as point P2.

Additional detents may be positioned in the degree of freedom of the knob in successive positions, represented along axis d. For example, curve 326 represents another detent that is encountered shortly after leaving the previous detent curve 324 when turning the knob in a particular direction.

A problem occurring with closely spaced detents is that often the user moves the knob from a first detent to a second detent but unintentionally moves the knob past the second detent due to the assistive detent forces of the second detent. This is because the force from the user required to move the knob past the resistive force of the first detent curve is combined with the assistive force of the second detent curve, causing the knob to unintentionally move past the second origin and past the endpoint of the second detent curve. Furthermore, the same problem occurs when the user moves the knob in the opposite direction, from the second detent to the first detent. The user must exert force to overcome the resistance at the last point of the second detent curve, which causes the knob to quickly move past the first point of the first detent curve, where the assistive force is added to the motion to cause the knob to unintentionally move past the last encountered point of the first detent.

Fig. 15b shows a detent force profile of the present invention in which the detent forces of two successive detents are partially overlapped due to the detents, and provide a hysteresis-like force effect. The two detent curves 328 and 330 are identical, thus allowing a single force command to create the multiple detents if desired. Endpoint 331 of curve 328 is positioned at position P1 and endpoint 332 of curve 328 is positioned at position P2, where P2 is about the same distance from origin O1 as P1. Similarly, endpoint 334 of curve 330 is positioned at position P3 and endpoint 333 of curve 330 is positioned at position P4, where P4 is about the

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same distance from origin O2 as P3. Detent curve 328 ends at endpoint 332 on the right side of origin O1 and within the range of forces of detent curve 330. Preferably, the end point 332 of curve 328 is positioned well after the endpoint 334 of curve 330, such that the point 332 has a position in the middle of the range between point 334 and the origin O2. The overlapped zone is between positions P3 and P2. In addition, the end point 332 of the first detent preferably does not extend past the origin O2 of the second detent into the positive side of the second detent. If another detent is positioned further on the d axis after curve 330, the end point 333 of curve 330 preferably is positioned well after the starting endpoint of the next detent curve and not past the origin of the next detent curve. Similar positioning can be provided for curves before curve 328 on axis d.

To solve the problem of unintentionally moving past a successive detent, the range of the second or successive detent is adjusted such that a lesser magnitude is preferably output at the beginning of the successive detent than would normally be output if the entire curve of the successive detent were used. Furthermore, the force detent curve used to output force is preferably different depending on the direction of the knob, similar to a hysteresis effect. As shown in FIGURE 15c, when moving the knob so the knob position changes from left to right, the force at the beginning of the range of detent curve 330 is at point 335 having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint 333 of the range of curve 330 (ignoring the signs or direction of the forces). Of course, in other embodiments point 335 can have a magnitude of other fractions of M, such as one-third or three-fourths of M. Additional curve 327 can be similarly positioned and provide a similar overlap with curve 330, and additional curves may be added before curve 328 and/or after curve 327.

As shown in FIGURE 15d, when moving the knob in the other direction so the knob position changes from right to left, the endpoints of the curve 330 reverse in magnitude with respect to the endpoints shown in Fig. 15c. In Fig. 15d, starting from origin O2, the force at the beginning of the range of detent curve 328 is at point 336 having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint 331 of curve 328 (other fractions of M can be provided for endpoint 336 in other embodiments). Any additional curves, such as curve 327, can be provided with a similar overlap. The force output on the knob thus changes depending on the direction of the knob. In a digital sensing system (e.g. using a digital encoder), the direction can be determined from a history of sensed values. For example, one or more sensed position values can be stored and compared to a current sensed position to determine the knob direction.

The use of a lesser magnitude at the beginning of the second detent reduces the tendency of the user to unintentionally skip past a second detent after moving the knob over a first detent closely spaced to the second detent. For example, when moving the knob left to right (e.g., clockwise) from position P1, a first detent (curve 328) ends at point 332 of curve 328, after

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which the force magnitude of point 335 on curve 330 begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point 334, i.e. the beginning point of the full curve 330. Thus, less force is assisting the user to move toward the origin O2 of curve 330 than if the force magnitude for beginning point 334 of the curve 330 were in effect. With less force assisting motion toward origin O2, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O2. Furthermore, the changing of endpoints of the detent curve, as dependent on direction, provides a hysteresis-like effect the reduces the unintentional skip in both directions. Thus, when moving the knob from right to left (e.g., counterclockwise) starting at origin O2, a first detent (curve 330) ends at point 334 of curve 330, after which a magnitude of point 336 on curve 328 begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point 334. Thus, less force is assisting the user to move toward the origin O1 of curve 328 than if the force magnitude for beginning point 332 of the curve 328 were in effect. With less force assisting motion toward origin O1, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O1.

The same overlapping and hysteresis feature can be provided for differently-shaped detents as well, such as curved detents of Figs. 16a-16e, detents having deadbands around the origin O, and/or other-shaped force profiles. In embodiments having detent endpoints that are spaced further apart, or which have very gradually-sloping curves, the overlap and hysteresis may not be needed since there may be enough space in the degree of freedom for the user to control the knob from unintentionally moving past the next detent.

FIGURE 16a is a graph illustration 337 of a periodic wave 339 that can be used to provide a variety of detent force sensations for use with the knob control device of the present invention. The periodic wave represents force exerted on the knob (axis F) vs. the position or displacement (axis d) of the knob, similar to the force detent profile shown in Figs. 15a and 15b. The wave 339 is a periodic function, such as a sine wave, triangle wave, square wave, etc. In Fig. 16a, a sine wave shape is shown. In the present invention, a portion of the wave may be used to provide detent and other force sensations for the knob 218 or 234. Various parameters of the sine wave are shown in Fig. 16a, including period and magnitude.

Curve 338 (solid line) represents a detent force effect that has been created based on the sine wave 339. Curve 338 has a width, which is the amount of the wave 339 along axis d used for the force detent. The location of the detent is the position in the degree of freedom at which the detent force is centered, i.e. the location of the origin position O of the detent. A deadband can be defined to be a distance from the origin O to a specified point, a region in which zero forces are output on the knob. Thus, the curve 338 shown in Fig. 16a shows a detent force starting at a magnitude M1 at location P1 and, when the knob is moved toward the origin O, the force increases to the maximum point M2 at location P2 and then decreases until point P3, where

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the deadband is reached (zero magnitude). Similarly, at point P4 on the other side of the origin O, the force increases from zero to a maximum magnitude M5 at location P5, after which the force drops a short distance to magnitude M6 at location P6. The force then drops to zero for increasing d, until another detent effect is encountered. The small decreases in force magnitude from the maximum magnitude at the end points of the curve 338 are useful in some detent embodiments to provide a less extreme assistive or resistive force to the user when entering or exiting the detent range, e.g., to gradually lead the user into the detent range before outputting the maximum force. This can provide a smoother-feeling and, in some cases, a more easily-selected detent (i.e., it can be easier to position the knob at the detent's origin).

The detent curve 338 can thus be defined using the parameters shown in Fig. 16a. For example, a force command protocol can provide a number of different commands that can cause the output of different force sensations to the user. The commands can each include a command identifier followed by one or more command parameters that define and characterize the desired force sensation. An example of a command defining a detent curve 338 is as follows:

DETENT (TYPE, PERIOD, MAGNITUDE, LOCATION, DEADBAND, FLAG, WIDTH, PHASE, OFFSET, LOCATION, INCREMENT, ARRAY POINTER)

The DETENT identifier indicates the type of force sensation. The TYPE parameter indicates a type of periodic wave from which to base the force detent curve, such as a sine wave, triangle wave, square wave, ramp, etc. The PERIOD and MAGNITUDE parameters define those characteristics of the periodic wave. The LOCATION parameter defines the location of the origin position for the detent in the degree of freedom of the knob. The DEADBAND parameter indicates the size of the deadband around the origin position. The FLAG parameter is a flag that indicates whether the detent is provided on the positive side, the negative side, or both sides around the location (origin position). The WIDTH parameter defines the amount of the wave 339 used for the detent curve, i.e. the extent of the wave used starting from the PHASE position. The PHASE parameter indicates the starting position of the detent curve 338 on the wave 339 (and is described in greater detail below). The OFFSET parameter indicates the amount of magnitude offset that curve 338 includes from the d axis, and is described in greater detail below. The INCREMENT parameter indicates the distance in the degree of freedom of the knob between successive detent locations. The optional LOCATION ARRAY POINTER parameter indicates a location in a separate array that has been previously programmed with the particular positions in the degree of freedom of the knob at which the detents are located and (optionally) the total number of detents; the array can be provided in memory, such as RAM, or other writable storage device. For example, the array can be preprogrammed with three detents, at locations of 45 degrees, 78 degrees, and 131 degrees in the rotation of the knob. The array can be accessed as necessary to retrieve these locations at which detent forces are to be output. This

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can be useful when the detent locations are not evenly or regularly spaced in the degree of freedom, and/or when a particular number of detents is desired to be output.

Furthermore, in other embodiments, a periodic wave can be additionally "shaped" to form a particular detent curve. For example, an "envelope" can be applied to a periodic wave to shape the wave in a particular way. One method of shaping a wave is to define a first magnitude and a settle width, which is the distance required for the wave to settle to a second, lesser magnitude from the first magnitude. This settle width thus provides a ramping shape to the upper and/or lower portions of the periodic wave about axis d. Although such shaping is performed in a spatial domain, it is similar to shaping a signal in the time domain. The shaping can be specified by parameters in a commands, such as a settled width parameter, magnitude parameters, etc.

The detent command can be sent by a supervisory microprocessor to a lower-level local microprocessor to decode and interpret the commands to control procedures provided in device 210 in firmware or other storage medium, as described with reference to Fig. 17 below. If a host computer and local microprocessor are used, the host computer can send the command to the local microprocessor, which parses/decodes and interprets the command and causes appropriate forces to be output. Commands and protocols for use in force feedback are described in greater detail in U.S. Patent 5,734,373, incorporated by reference herein. Such commands can also be retrieved from a storage device such as memory and then parsed and interpreted by a local microprocessor.

The ability to define a force detent (in the spatial domain) in terms of a periodic waveform can be useful in force feedback implementations in which periodic force effects in the time domain are also provided. For example, vibration force sensations can be provided by outputting a periodic sine wave or square wave for the magnitude of the force over time. If such time-based effects can be output on knob 218 or 234, then it is convenient to use the same periodic wave definitions and data for defining force vs. position profiles for detents as shown in Figs. 16a-16e.

FIGURE 16b is a graph illustration 340 showing particular parameters of the detent command described above which are applied to a periodic wave. Sine wave 342 has a magnitude and period as shown. A specified phase of the desired detent curve causes the detent curve to start at a position on wave 342 in accordance with the phase. For example, in Fig. 16b, a phase of 50 degrees is specified. This will cause the resulting detent curve to start at point P on the wave 342. A width parameter specifies the amount of the wave from the phase location to be used as the detent curve. Furthermore, an offset of -0.8 is indicated. This causes the resulting detent curve to be shifted down by 80% from the wave 342. Furthermore, a deadband is also specified (not shown in Fig. 16b.).

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FIGURE 16c is a graph 344 showing the resulting detent curve 346 obtained from the application of the parameters to the wave 342 described with reference to Fig. 16b. The portion of the wave 342 starting at the phase and positioned above the offset line in Fig. 16b is used in the detent curve 346. Furthermore, a deadband 348 has been added to the curve. The flag in the detent command has caused the positive side of the curve 346 to be mirrored on the negative side of the origin O. This detent curve 346 causes a detent force that is similar to the detent force described with reference to Fig. 16a, only smaller in magnitude and in position range over the degree of freedom of the knob.

FIGURE 16d is a graph 360 showing a periodic wave and parameters to be applied to the wave. Sine wave 362 is provided as described above, having a particular period and magnitude. An offset is specified for the resulting detent curve; in the example of Fig. 16d, the offset is 1, thus causing the detent curve to be shifted upward by its entire magnitude. A phase of 270 degrees is also indicated, so that the detent curve starts at the lowest magnitude of the wave 372 at point P. Furthermore, an increment is also specified as a parameter (not shown). FIGURE 16e is a graph 370 illustrating the detent curves 372 and 374 resulting from the wave 362 and parameters described with reference to Fig. 16d. The portion of the wave 362 past point P and ending at a point defined by a width parameter is provided both on the positive side and the negative side of origin O1 of graph 370 for curve 372 (the positive and negative sides are designated by the flag parameter). A second curve 374 is also shown, where the origin O2 of the second curve is positioned at a distance from the origin O1 as specified by the increment parameter. Additional curves similar to curves 372 and 374 are provided at further distances at same increment from each other. The detent curves 372 and 374 provide a much steeper, less gradual detent force over the detent range than the other detent forces shown in Figs. 16a and 16c. Furthermore, no actual deadband is specified, although the shape of each half of the curve 372 provides a small zone 376 where zero force is output, similar to a deadband.

FIGURE 17 is a block diagram illustrating an electromechanical system 400 for the device 210 of Fig. 10 suitable for use with the present invention. A force feedback system including many of the below components is described in detail in Patent number 5,734,373.

In one embodiment, device 210 includes an electronic portion having a local microprocessor 402, local clock 404, local memory 406, sensor interface 408, and actuator interface 410.

Local microprocessor 402 is considered local to device 210 and is preferably similar in type and function to microprocessor 90, described above. Microprocessor 402 can include one microprocessor chip, or multiple processors and/or co-processor chips, and can include digital signal processor (DSP) functionality. Also, "haptic accelerator" chips can be provided which

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are dedicated to calculating velocity, acceleration, and/or other force-related data. Alternatively, fixed digital logic and/or state machines can be used to provide similar functionality.

A local clock 404 can be coupled to the microprocessor 402 to provide timing data, for example, to compute forces to be output by actuator 270; or timing data for microprocessor 402 can be retrieved from the USB interface. Local memory 406, such as RAM and/or ROM, is preferably coupled to microprocessor 402 in interface device 210 to store instructions for microprocessor 402, temporary and other data, calibration parameters, adjustments to compensate for sensor variations, and/or the state of the device 210. Display 214 can be coupled to local microprocessor 402 in some embodiments. Alternatively, a different microprocessor or other controller can control output to the display 214.

Sensor interface 408 may optionally be included in device 210 to convert sensor signals to signals that can be interpreted by the microprocessor 402. Alternately, microprocessor 402 can perform these interface functions. Actuator interface 410 can be optionally connected between the actuator 270 and microprocessor 402 to convert signals from microprocessor 402 into signals appropriate to drive the actuators. Actuator interface 410 can include power amplifiers, switches, digital to analog controllers (DACs), and other components, as well known to those skilled in the art. In alternate embodiments, actuator interface 410 circuitry can be provided within microprocessor 402 or in the actuator 270. A power supply 412 can be coupled to actuator 270 and/or actuator interface 410 to provide electrical power. In a different embodiment, power can be supplied to the actuator 270 and any other components (as required) by an interface bus. Power can also be stored and regulated by device 210 and thus used when needed to drive actuator 270.

A mechanical portion is included in device 210, an example of which is shown above in Figs. 12a-12b and 13a-13c. The mechanical portion can include some or all of the components needed for rotational motion of knob 218, transverse motion of knob 218, the push and/or pull motion of knob 218, and force feedback in any or all of these degrees of freedom of the knob.

Mechanical portion 400 preferably includes sensors 414, actuator 270, and mechanism 416. Sensors 414 sense the position, motion, and/or other characteristics of knob 218 along one or more degrees of freedom and provide signals to microprocessor 402 including information representative of those characteristics. Typically, a sensor 414 is provided for each degree of freedom along which knob 218 can be moved, or, a single compound sensor can be used for multiple degrees of freedom. Sensors 414 can include sensor 276, switch 252, and switch 258 as shown in Figs. 12a-12b. For example, one switch 252 of Figs. 12a-12b or switch 290 of Fig. 13c can include a sensor switch for each transverse direction 228 that the knob 218 can be moved. Examples of sensors suitable for rotary sensor 276 of Figs. 12a-12b and 13a-13c include optical encoders, analog sensors such as potentiometers, Hall effect magnetic sensors, optical sensors

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such as a lateral effect photo diodes, tachometers, and accelerometers. Furthermore, both absolute and relative sensors may be used.

In those embodiments including force feedback, actuator 270 transmits forces to knob 218 in one or more directions in a rotary degree of freedom in response to signals output by microprocessor 402 or other electronic logic or device, i.e., it is "electronically-controlled." The actuator 270 produces electronically modulated forces which means that microprocessor 402 or other electronic device controls the application of the forces. Typically, an actuator 270 is provided for each knob 218 that includes force feedback functionality. In some embodiments, additional actuators can also be provided for the other degrees of freedom of knob 218, such as the transverse motion of the knob 18 and/or the push or pull motion of the knob. The actuators, such as actuator 270, can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), voice coil actuators, etc. Passive actuators can also be used, including magnetic particle brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. In some embodiments, all or some of sensors 414 and actuator 270 can be included together as a sensor/actuator pair transducer, as shown in Figs. 12a-12b for actuator 270 and sensor 276.

Mechanism 416 is used to translate motion of knob 218 to a form that can be read by sensors 414, and, in those embodiments including force feedback, to transmit forces from actuator 270 to knob 218. Examples of mechanism 416 are shown with respect to Figs. 12a-12b and 13a-13c. Other types of mechanisms can also be used, as disclosed in U.S. Patent Nos. 5,767,839, 5,721,566, 5,805,140, all incorporated by reference herein. Also, a drive mechanism such as a capstan drive mechanism can be used to provide mechanical advantage to the forces output by actuator 270, as described in patent no. 5,731,804, incorporated by reference herein. Alternatively, a belt drive system, gear system, or other mechanical amplification/transmission system can be used.

Other input devices 420 can be included in interface device 210 and send input signals to microprocessor 402. Such input devices can include buttons, such as buttons 216 on front panel 212 as shown in Fig. 10, used to supplement the input from the knob to the device 210. Also, dials, switches, voice recognition hardware (e.g. a microphone, with software implemented by microprocessor 402), or other input mechanisms can be used. can also be included to send a signal (or cease sending a signal) to microprocessor 402 or to the actuator 270 or actuator interface 410, indicating that the user is not gripping the knob 218, at which point all output forces are ceased for safety purposes. A safety or "deadman" switch 422 can optionally be included for the knob 218 in those implementations providing force feedback on the knob. Such a safety switch can be implemented similarly to safety switch 115 described above with

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reference to Fig. 4. Safety switches are also described in patent no. 5,691,898. incorporated by reference herein.

Other microprocessor 424 can be included in some embodiments to communicate with local microprocessor 402. Microprocessors 402 and 424 are preferably coupled together by a bi-directional bus 426. Additional electronic components may also be included for communicating via standard protocols on bus 426. These components can be included in device 210 or another connected device. Bus 426 can be any of a variety of different communication busses. For example, a bi-directional serial or parallel bus, a wireless link, a network architecture (such as Canbus), or a uni-directional bus can be provided between microprocessors 424 and 402.

Other microprocessor 424 can be a separate microprocessor in a different device or system that coordinates operations or functions with the device 210. For example, other microprocessor 424 can be provided in a separate control subsystem in a vehicle or house, where the other microprocessor controls the temperature system in the car or house, or the position of mechanical components (car mirrors, seats, garage door, etc.), or a central display device that displays information from various systems. Or, the other microprocessor 424 can be a centralized controller for many systems including device 210. The two microprocessors 402 and 424 can exchange information as needed to facilitate control of various systems, output event notifications to the user, etc. For example, if other microprocessor 424 has determined that the vehicle is overheating, the other microprocessor 424 can communicate this information to the local microprocessor 202, which then can output a particular indicator on display 214 to warn the user. Or, if the knob 218 is allowed different modes of control, the other microprocessor 424 can control a different mode. Thus, if the knob 218 is able to control both audio stereo output as well as perform temperature control, the local microprocessor 402 can handle audio functions but can pass all knob sensor data to other microprocessor 424 to control temperature system adjustments when the device 210 is in temperature control mode.

In other embodiments, other microprocessor 424 can be a microprocessor in a host computer, for example, that commands the local microprocessor 402 to output force sensations by sending host commands to the local microprocessor. The host computer can be a personal computer, workstation, video game console, or other computing or display device as described in previous embodiments. The host computer can implement a host application program with which a user interacts using knob 218 and/or other controls and peripherals. The host application program can be responsive to signals from knob 218 such as the transverse motion of the knob, the push or pull motion, and the rotation of the knob (e.g., the knob 218 can be provided on a game controller or interface device such as a game pad, joystick, steering wheel, or mouse that is connected to the host computer). In force feedback embodiments, the host application program can output force feedback commands to the local microprocessor 402 and to the knob 218. In a host computer embodiment or other similar embodiment, microprocessor 402

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can be provided with software instructions to wait for commands or requests from the host computer, parse/decode the command or request, and handle/control input and output signals according to the command or request.

For example, in one force feedback embodiment, host microprocessor 424 can provide low-level force commands over bus 426, which microprocessor 402 directly transmits to the actuators. In a different force feedback local control embodiment, host microprocessor 424 provides high level supervisory commands to microprocessor 402 over bus 426, and microprocessor 402 manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer, similar to the embodiments for wheel 16 described above.

In an alternate embodiment, no local microprocessor 402 is included in interface device 210, and a remote microprocessor, such as microprocessor 424, controls and processes all signals to and from the components of interface device 210. Or, hardwired digital logic can perform any input/output functions to the knob 218.

While this invention has been described in terms of several preferred embodiments, it is contemplated that alterations, permutations and equivalents thereof will become apparent to those skilled in the art upon a reading of the specification and study of the drawings. For example, many types of actuators, sensors, and mechanisms can be used to sense and apply forces on the wheel or knob. In addition, the wheel or knob itself can be implemented in a variety of ways, as a dial, cylinder, knob, sphere, or other shape. Also, a great variety and types of force sensations can be output on wheel 16. It should also be noted that the embodiments described above can be combined in various ways in a particular implementation. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. It is therefore intended that the following appended claims include all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.

What is claimed is:

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CLAIMS

1. An interface device for interfacing a user's input with a host computer and providing force feedback to said user, said interface device comprising:

a user manipulandum contacted and manipulated by a user and moveable in a planar workspace with respect to a ground surface;

a manipulandum sensor coupled to said user manipulandum for detecting a position of said user manipulandum in said planar workspace and operative to send a position signal to said host computer indicating a position of said user manipulandum in said workspace;

a rotatable wheel coupled to said user manipulandum and rotatable about a wheel axis;

a wheel sensor coupled to said wheel and providing a wheel signal to said host computer indicating a rotary position of said wheel;

a wheel actuator coupled to said rotatable wheel and operative to apply a computer-modulated force to said rotatable wheel about said wheel axis, wherein said force is modulated as a function of time or wheel position about said wheel axis.

2. An interface device as recited in claim 1 wherein said user manipulandum includes a mouse object.

3. An interface device as recited in claim 2 wherein said manipulandum sensor includes a ball and roller assembly.

4. An interface device as recited in claim 2 further comprising an actuator for applying a force to said user manipulandum in said workspace.

5. An interface device as recited in claim 2 wherein said rotary wheel rotates about an axis parallel to said planar workspace.

6. An interface device as recited in claim 2 wherein said wheel actuator is coupled to said wheel by a belt drive mechanism.

7. An interface device as recited in claim 2 wherein said wheel actuator is directly coupled to said wheel.

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8. An interface device as recited in claim 2 wherein said wheel can be depressed into a housing of said user manipulandum.

9. An interface device as recited in claim 2 wherein said wheel is coupled to a first shaft that is coupled to and rotatable about a second shaft, said second shaft being coupled to said wheel actuator.

10. An interface device as recited in claim 1 further comprising a local microprocessor, separate from host computer, coupled to said actuator and controlling said actuator to apply said computer-modulated force on said wheel.

11. An interface device as recited in claim 1 wherein said host computer is running a graphical environment and wherein said force applied to said wheel corresponds with an event or interaction displayed in said graphical environment.

12. An interface device as recited in claim 1 wherein said wheel actuator outputs a set of isotonic forces when said interface device is in an isotonic mode, and wherein said wheel actuator outputs a set of isometric forces when said interface device is in an isometric mode.

13. A handheld force feedback remote control device for providing input to an electronic device located remotely from said remote control device, the remote control device comprising:

a wheel rotatably coupled to a housing of said remote control device and rotatable about an axis, said wheel being manipulated by a user;

an actuator coupled to said wheel for outputting a computer-modulated force detent on said wheel, said force detent felt by said user, wherein said force detent is provided at a predetermined rotational position of said wheel; and

a sensor that senses rotation of said wheel and provides a wheel signal to said electronic device indicating a rotary position of said wheel.

14. A force feedback wheel device as recited in claim 13 wherein said force detent includes an attractive force for biasing said wheel to said predetermined rotational position

15. A force feedback wheel device as recited in claim 13 wherein said remote control device sends signals to said electronic device using wireless transmission of information using an electromagnetic beam.

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16. A force feedback wheel device as recited in claim 13 wherein said electronic device includes a video game console and wherein said remote control device includes a game controller for inputting signals to said video game console.

17. A force feedback wheel device as recited in claim 13 wherein additional forces can be applied to said wheel, said additional forces including at least one of a damping force sensation, an inertial force sensation, a friction force sensation, a spring force sensation, a force detent sensation, an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

18. A force feedback wheel device for providing input to an electronic radio, the wheel device comprising:

a wheel rotatably coupled to a housing of said electronic radio and rotatable about an axis, said wheel being manipulated by a user;

an actuator coupled to said wheel for outputting a computer-modulated force detent on said wheel, said force detent felt by said user, wherein said force detent is provided at a predetermined user-preferred rotational position of said wheel; and

a sensor that senses rotation of said wheel and provides a wheel signal to said electronic device indicating a rotary position of said wheel;

19. A force feedback wheel device as recited in claim 18 wherein said force detent includes an attractive force for biasing said wheel to said predetermined rotational position

20. A force feedback wheel device as recited in claim 18 wherein said predetermined user-preferred positions are positions of preferred radio station frequencies in a radio frequency range.

21. A force feedback wheel device as recited in claim 18 wherein additional forces can be applied to said wheel, said additional forces including at least one of a damping force sensation, a spring force sensation, an inertial force sensation, a friction force sensation, a force detent sensation, an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

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22. A method for providing a force feedback mouse wheel on a mouse interface device, said mouse interface device coupled to a host computer, the method comprising:

sensing a position of a mouse of said mouse interface device in a planar workspace and sending an indication of said position to a host computer;

sensing a rotation of said mouse wheel about an axis of rotation and sending a wheel signal to said host computer indicating a current position of said wheel about said axis; and

applying a force to said mouse wheel about said axis using a wheel actuator coupled to said mouse wheel, wherein said force is coordinated with an event occurring in said graphical environment.

23. A method as recited in claim 22 wherein said sensing a rotation of said mouse wheel includes sensing an absolute position of said mouse wheel about said axis.

24. A method as recited in claim 22 wherein said applying a force to said mouse wheel is commanded by a local microprocessor included in said mouse interface device and separate from said host computer.

25. A method as recited in claim 22 wherein said event is a scrolling of a displayed document as controlled by said sensed rotation of said mouse wheel and said wheel signal.

26. A method as recited in claim 22 wherein said event is an interaction of a cursor with a graphical object implemented by said host computer, said cursor having motion influenced by said rotation of said wheel.

27. A method as recited in claim 26 wherein said interaction is a collision of said cursor with said graphical object.

28. A method as recited in claim 22 wherein said force is one of a damping force sensation, an inertial force sensation, and a friction force sensation.

29. A method as recited in claim 22 wherein said force is a force detent sensation.

30. A method as recited in claim 22 wherein said force is one of an obstruction force sensation, a texture sensation, a jolt sensation, and a vibration sensation.

31. A method as recited in claim 22 further comprising applying a force to said mouse object in said planar workspace using an actuator different from said wheel actuator.

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32. A knob controller device comprising:

a knob coupled to a grounded surface, said knob rotatable in a rotary degree of freedom about an axis extending through said knob, said knob also moveable in a transverse direction approximately perpendicular to said axis;

a rotational sensor that detects a position of said knob in said rotary degree of freedom;

a transverse sensor operative to detect a position of said knob in said transverse direction; and

an actuator coupled to said knob and operative to output a force in said rotary degree of freedom about said axis.

33. A knob controller device as recited in claim 32 wherein said knob is also moveable in a linear degree of freedom approximately parallel to said axis, and further comprising a linear sensor operative to detect a position of said knob in said linear degree of freedom.

34. A knob controller device as recited in claim 33 wherein said knob can be pushed or pulled by a user, said pushing or pulling motion being detected by said linear sensor.

35. A knob controller device as recited in claim 32 wherein said knob is moveable in a plurality of transverse directions, and wherein said transverse sensor is operative to detect when said knob is moved in any of said transverse directions.

36. A knob controller device as recited in claim 32 wherein said transverse sensor includes a hat switch having a plurality of individual switches, each of said individual switches detecting movement of said knob in a particular transverse direction.

37. A knob controller device as recited in claim 36 wherein said knob is moveable in four transverse directions spaced approximately orthogonal to each other, and wherein said hat switch includes four individual switches.

38. A knob controller device as recited in claim 32 further comprising a microprocessor coupled to said rotational sensor and to said transverse sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor signals.

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39. A knob controller device as recited in claim 38 wherein said device is an audio device.

40. A knob controller device as recited in claim 32 further comprising a microprocessor coupled to said rotational sensor and to said transverse sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor signals, said microprocessor sending force feedback signals to said actuator to control forces output by said actuator.

41. A knob controller device as recited in claim 32 further comprising a display, wherein an image on said display is changed in response to manipulation of said knob in said transverse direction.

42. A knob controller device as recited in claim 32 wherein a flexible member is coupled between said knob and said actuator to allow said movement in said transverse direction.

43. A knob controller device as recited in claim 42 wherein said flexible member is a spring member.

43. A knob controller device as recited in claim 42 wherein said flexible member includes a base plate and a plurality of bent flexible portions coupled to said base plate.

44. A knob controller device comprising:

a knob coupled to a grounded surface, said knob rotatable in a rotary degree of freedom about an axis extending through said knob, said knob also moveable in a linear degree of freedom approximately parallel to said axis;

a rotational sensor that detects a position of said knob in said rotary degree of freedom;

a linear sensor that detects a position of said knob in said linear degree of freedom; and

an actuator coupled to said knob and operative to output a force in said rotary degree of freedom about said axis.

45. A knob controller device as recited in claim 44 further comprising a microprocessor coupled to said rotational sensor and to said linear sensor, said microprocessor receiving sensor signals from said sensors and controlling a function of a device in response to said sensor

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signals, said microprocessor sending force feedback signals to said actuator to control forces output by said actuator.

46. A knob controller device as recited in claim 44 wherein said knob can be pushed by a user, said pushing motion being detected by said linear sensor.

47. A knob controller device as recited in claim 44 wherein said knob can be pulled by a user, said pulling motion being detected by said linear sensor.

48. A knob controller device as recited in claim 44 wherein said knob can be pushed or pulled by a user, said pushing motion and said pulling motion being detected by said linear sensor.

49. A knob controller device as recited in claim 44 said knob is also moveable in a plurality of transverse directions approximately perpendicular to said axis, and further comprising a transverse sensor operative to detect movement of said knob in any of said transverse directions.

50. A knob controller device as recited in claim 44 further comprising a spring member for biasing said knob to a center position in said linear degree of freedom.

51. A knob controller device as recited in claim 44 wherein said linear sensor detects a position of said knob within a detectable continuous range of motion of said knob, and wherein said linear sensor outputs a sensor signal indicative of said position.

52. An interface control device including force feedback and providing rate control and position control modes, the interface control device comprising:

a knob grasped by a user and movable in a degree of freedom;

an actuator coupled to said knob and providing forces on said knob in said degree of freedom;

a sensor that detects a position of said knob in said degree of freedom and outputs a sensor signal including information representing said position;

a microprocessor coupled to said actuator and to said sensor, said microprocessor controlling said forces provided by said actuator and receiving said sensor signal from said sensor, wherein said microprocessor commands either a position control mode or a rate control mode for said knob, wherein said position control mode controls a value based on a position of said knob in said degree of freedom, and wherein said rate control mode controls a rate of

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change of said value based on a position of said knob in said degree of freedom, wherein said rate control mode provides a force on said knob using said actuator, said force being applied in a direction opposing a movement of said knob away from an origin position.

53. An interface control device as recited in claim 52 wherein said degree of freedom is a rotary degree of freedom.

54. An interface control device as recited in claim 52 wherein said degree of freedom is a linear degree of freedom.

55. An interface control device as recited in claim 52 wherein said force opposing said movement is a spring force.

56. An interface control device as recited in claim 52 wherein said microprocessor controls said actuator to output at least one force detent during movement of said knob in said position control mode.

57. An interface control device as recited in claim 52 wherein said rate control mode is used to control the value of a volume, bass, treble, or balance function of said device.

58. An interface control device as recited in claim 52 wherein said position control mode is used to control the value of a volume, bass, treble, or balance function of said device.

59. An interface control device as recited in claim 52 wherein said rate control mode is used to control a position of a physical component in a vehicle.

60. A method for providing detent forces for a force feedback control, the method comprising:

outputting a first force for a first detent on a user manipulatable object contacted by a user and moveable in a degree of freedom, said first force being output when said user manipulatable object is moved within a range of said first detent, said first force being output by a electronically-controlled actuator, wherein said first force assists movement of said user manipulatable object toward an origin position of said first detent and wherein said first force resists movement of said user manipulatable object away from said origin position of said first detent; and

outputting a second force for a second detent on said user manipulatable object when said user manipulatable object is moved within a range of said second detent, said second force being

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output by said actuator and said second detent having an origin position different from said origin position of said first detent, wherein said second force assists movement of said user manipulatable object toward an origin position of said second detent and wherein said second force resists movement of said user manipulatable object away from said origin position of said second detent, wherein a portion of said range of said first detent overlaps a portion of said range of said second detent.

61. A method as recited in claim 60 wherein said first force for said first detent has a magnitude that increases the further that said user manipulatable object is positioned from said origin of said first detent, and wherein said second force for said second detent has a magnitude that increases the further that said user manipulatable object is positioned from said origin of said second detent.

62. A method as recited in claim 60 wherein a deadband is provided around said origin of said first detent and around said origin of said second detent, wherein a magnitude of said first force and said second force is zero when said user manipulatable object is positioned within said deadband.

63. A method as recited in claim 60 wherein when said user manipulatable object is moved in a particular direction from said first detent to said second detent, said first detent range has an endpoint positioned after a beginning point of said second detent range such that a force at said beginning point of said second detent range has less magnitude than a force at an endpoint of said second detent range.

64. A method as recited in claim 63 wherein when said user manipulatable object is moved in a direction opposite to said particular direction from said second detent to said first detent, a force at a first-encountered point of said first detent range has less magnitude than a force at a last-encountered point of said first detent range.

65. A method as recited in claim 63 wherein said first detent range does not overlap past said origin of said second detent.

66. A method as recited in claim 60 wherein said user manipulatable object is a knob and said degree of freedom is a rotary degree of freedom.

67. A method for providing detent forces for a force feedback control, the method comprising:

defining a periodic wave;

using at least a portion of said periodic wave to define a detent force curve, said detent force curve defining a force to be output on a user manipulatable object based on a position of

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said user manipulatable object in a degree of freedom, said user manipulatable object being contacted and moveable by a user; and

using said detent force curve to command said force on said user manipulatable object, said force being output by a electronically-controlled actuator.

68. A method as recited in claim 67 wherein said defining a periodic wave includes specifying a type, a period and a magnitude for said periodic wave.

69. A method as recited in claim 67 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying a portion of said periodic wave to define a width of said detent force curve.

70. A method as recited in claim 69 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying a phase and an offset to be applied to said periodic wave to define said detent force curve.

71. A method as recited in claim 67 wherein said using at least a portion of said periodic wave to define a detent force curve includes specifying an increment distance, wherein successive detent force curves in said degree of freedom are spaced apart by said increment distance.

72. A method as recited in claim 67 wherein said user manipulatable object is a knob moveable in a rotary degree of freedom.

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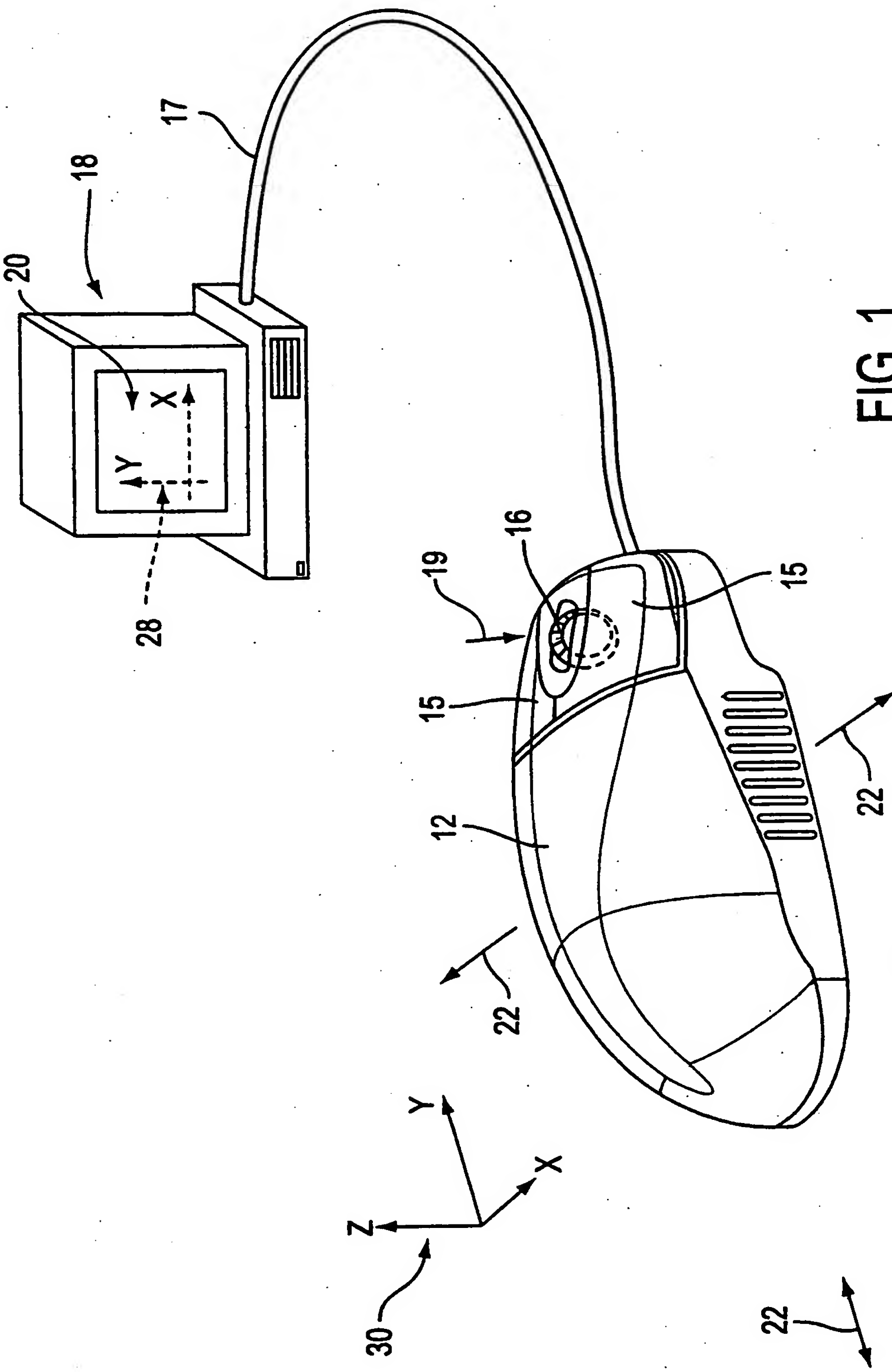

FIG. 1

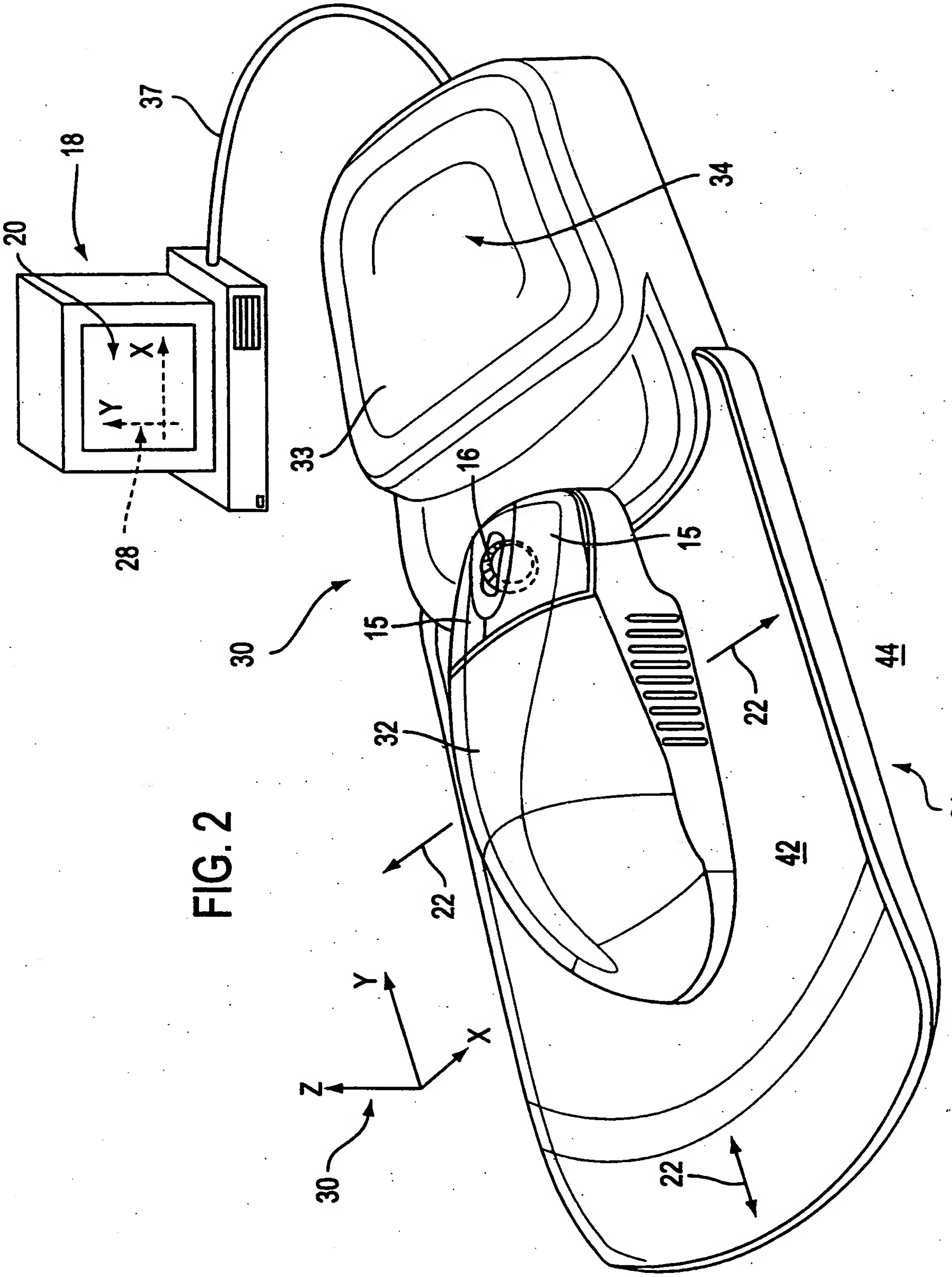

FIG. 2

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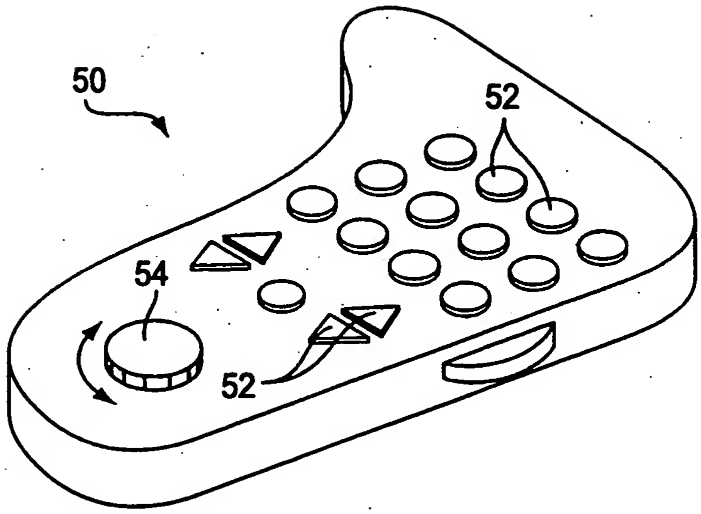
FIG. 3A



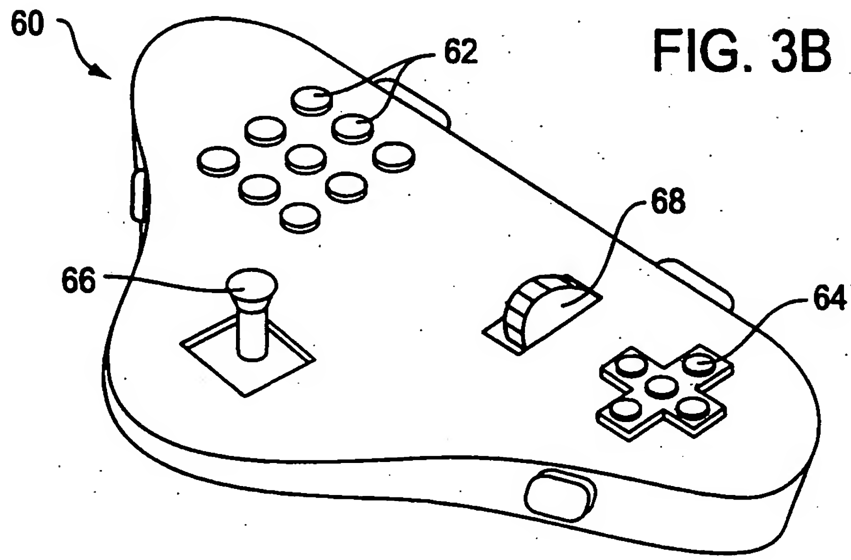


FIG. 3B

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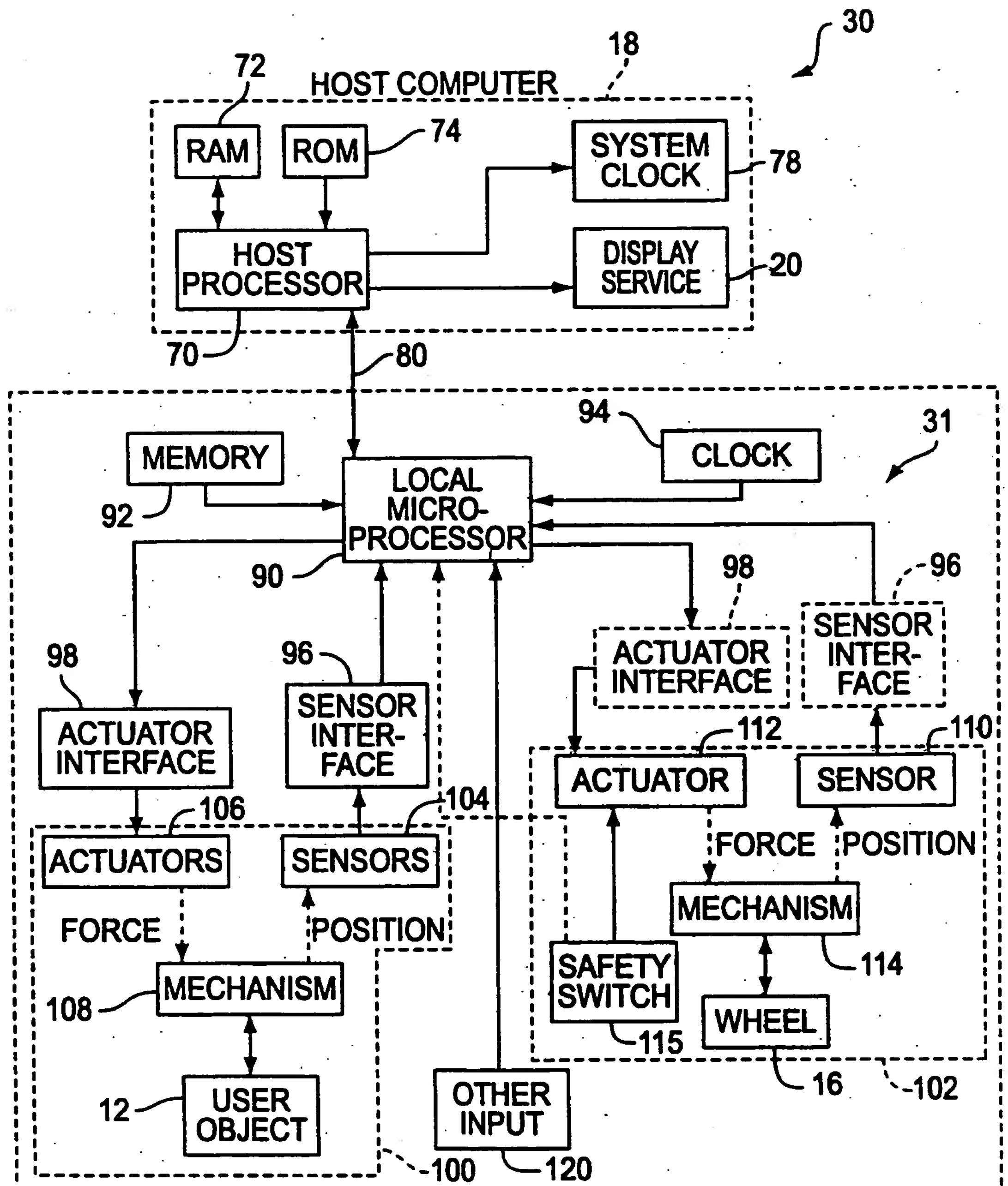


FIG. 4

BNSDOCID: <WO_________9949443A2_IA>

FIG. 5

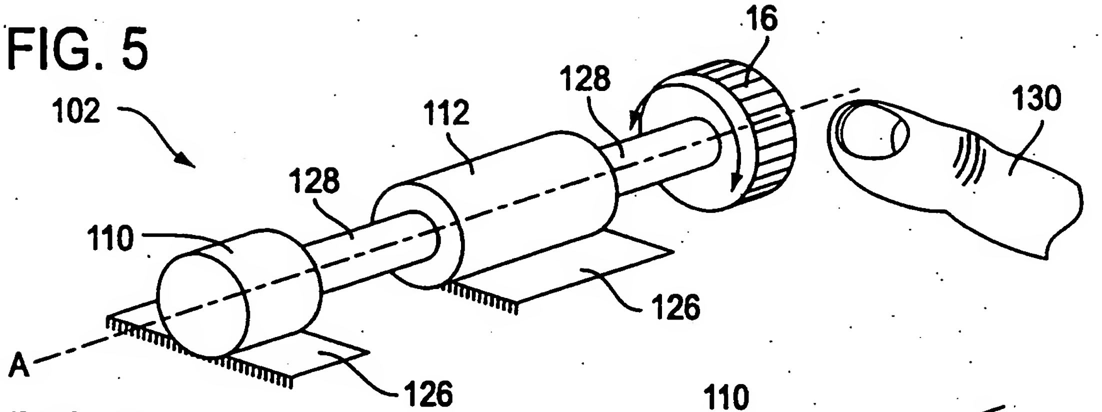


FIG. 6

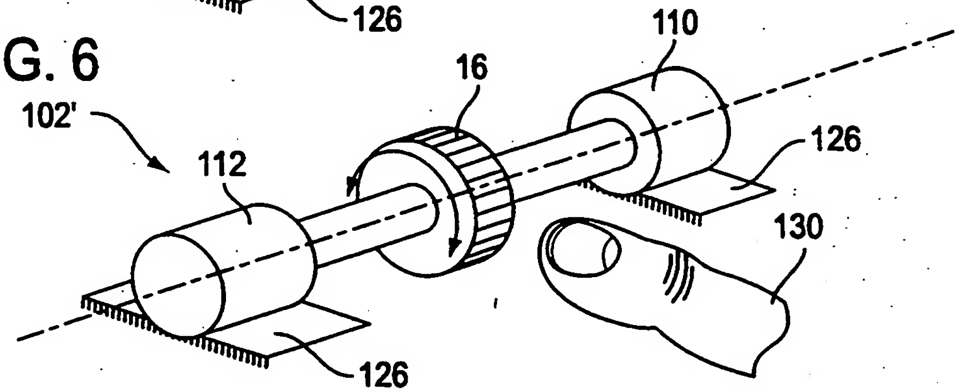


FIG. 7

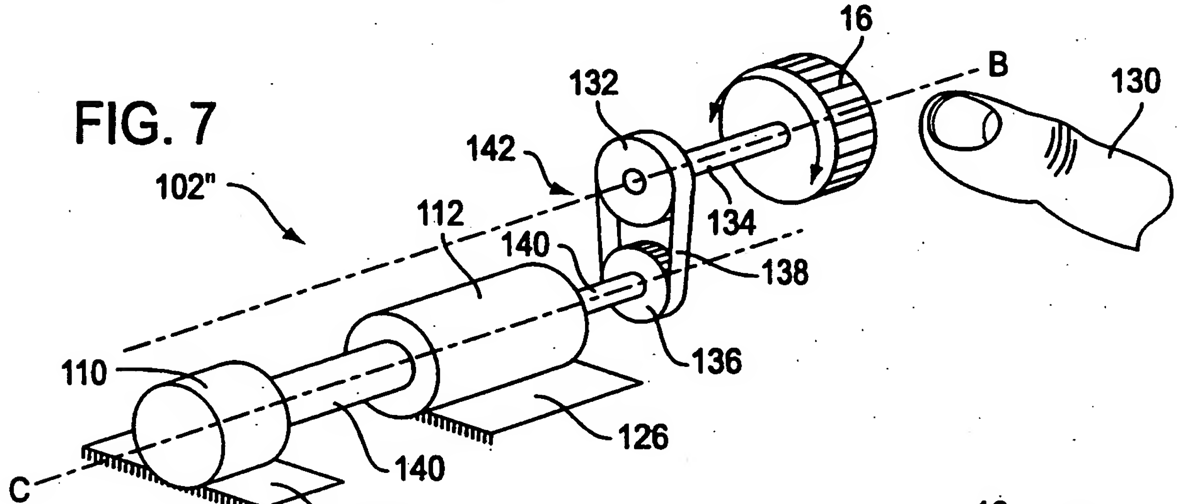
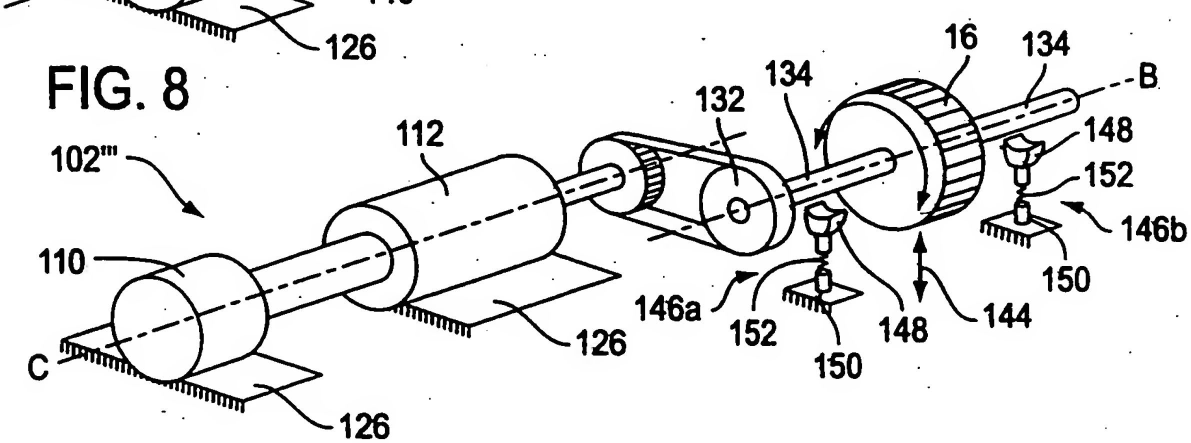


FIG. 8



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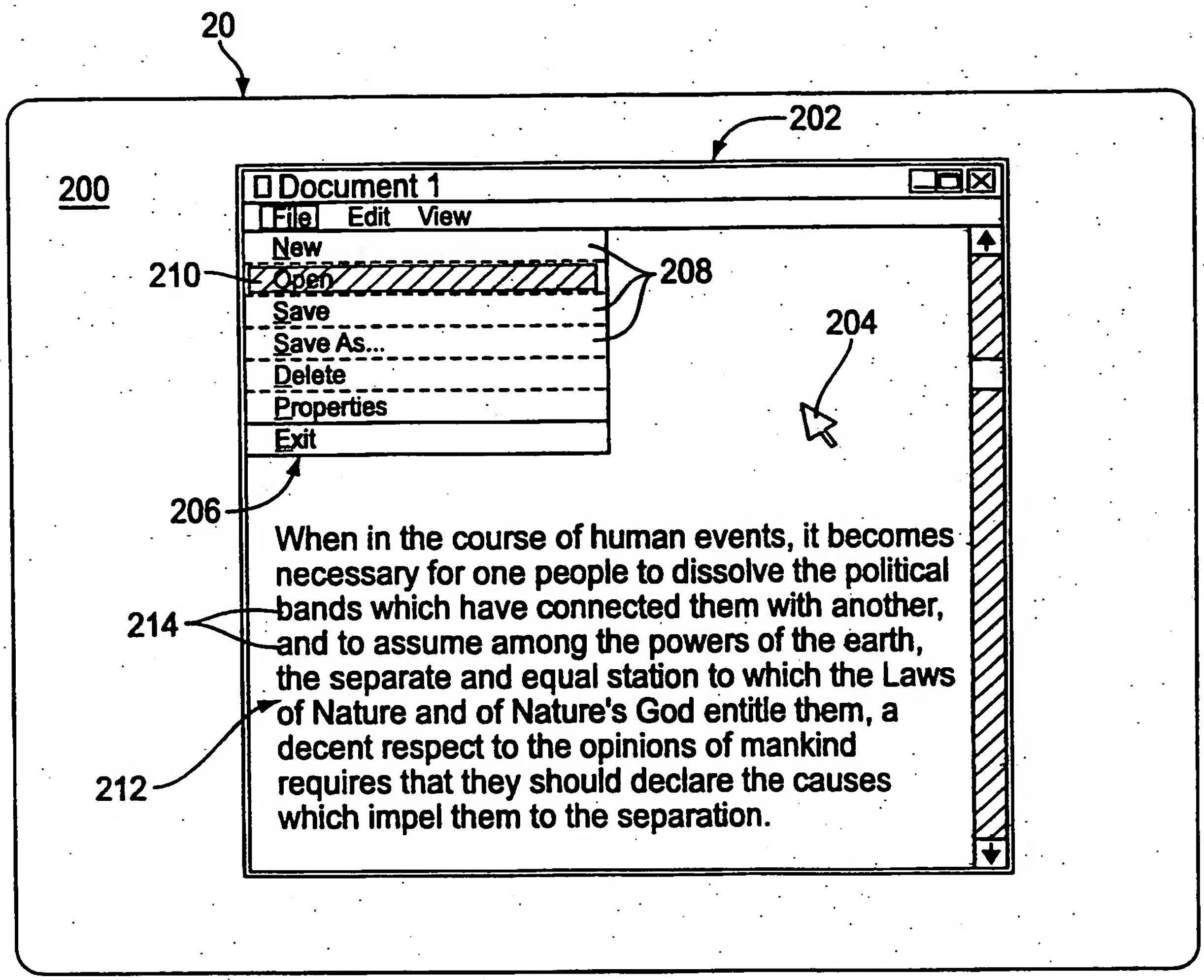
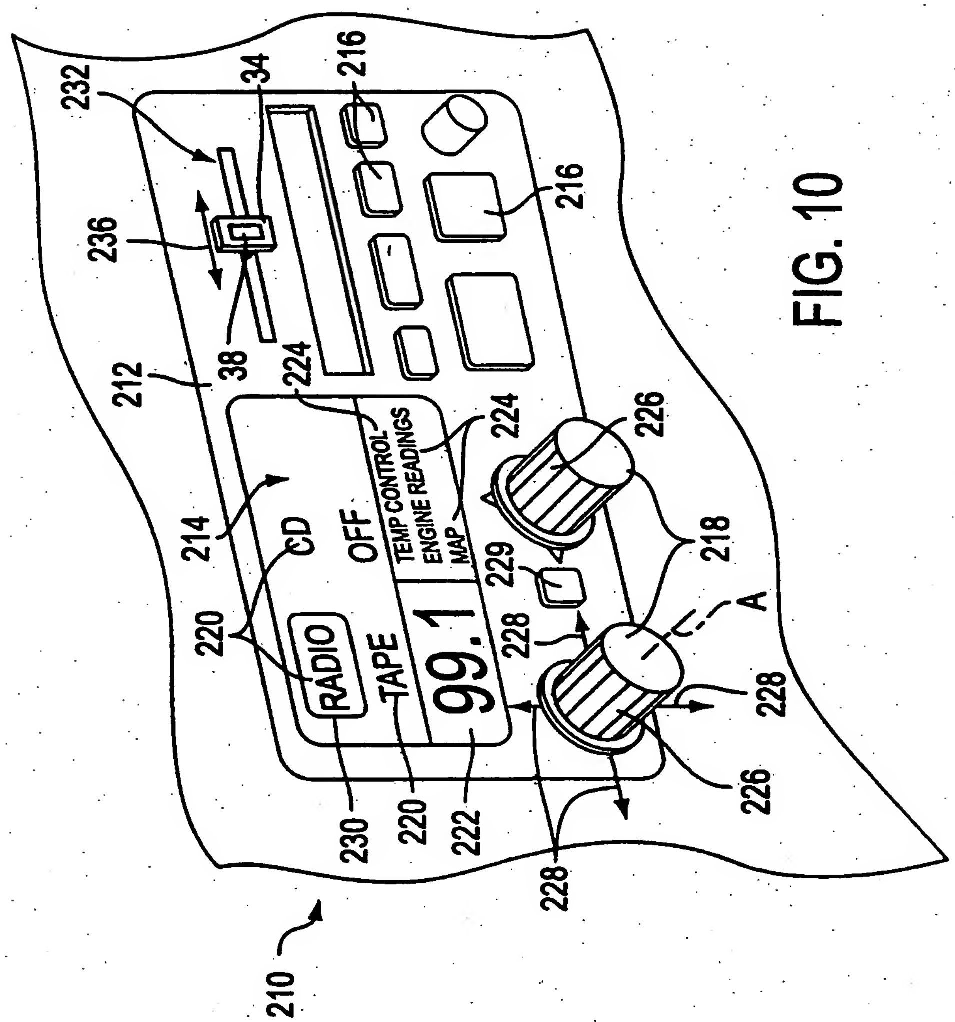

20
202
200
Document 1
File Edit View
New
Open
Save
Save As...
Delete
Properties
Exit
210
208
204
206
When in the course of human events, it becomes necessary for one people to dissolve the political bands which have connected them with another, and to assume among the powers of the earth, the separate and equal station to which the Laws of Nature and of Nature's God entitle them, a decent respect to the opinions of mankind requires that they should declare the causes which impel them to the separation.
214
212

FIG. 9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ENGINE READINGS
MAP
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CD
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TAPE
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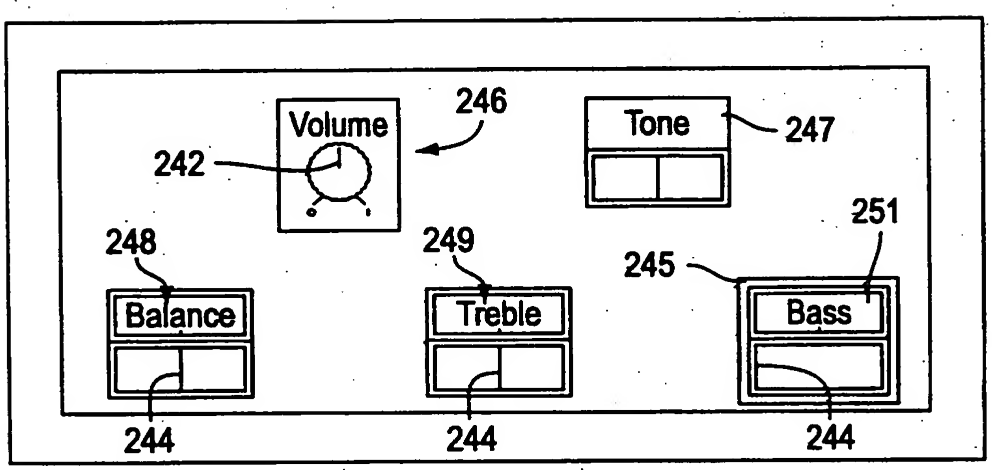
210

FIG. 10


Volume
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Tone
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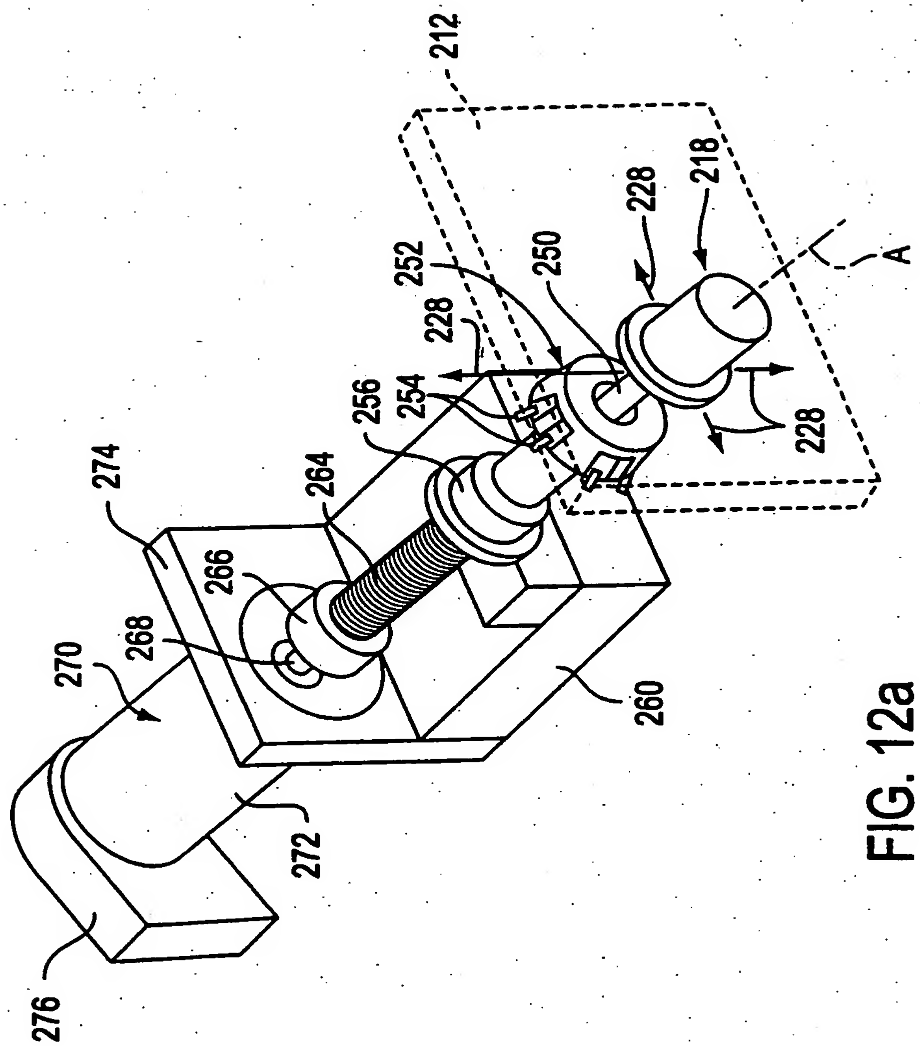
242
251
248
249
245
Balance
Treble
Bass
244
244
244

FIG. 11


212
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272
276

FIG. 12a

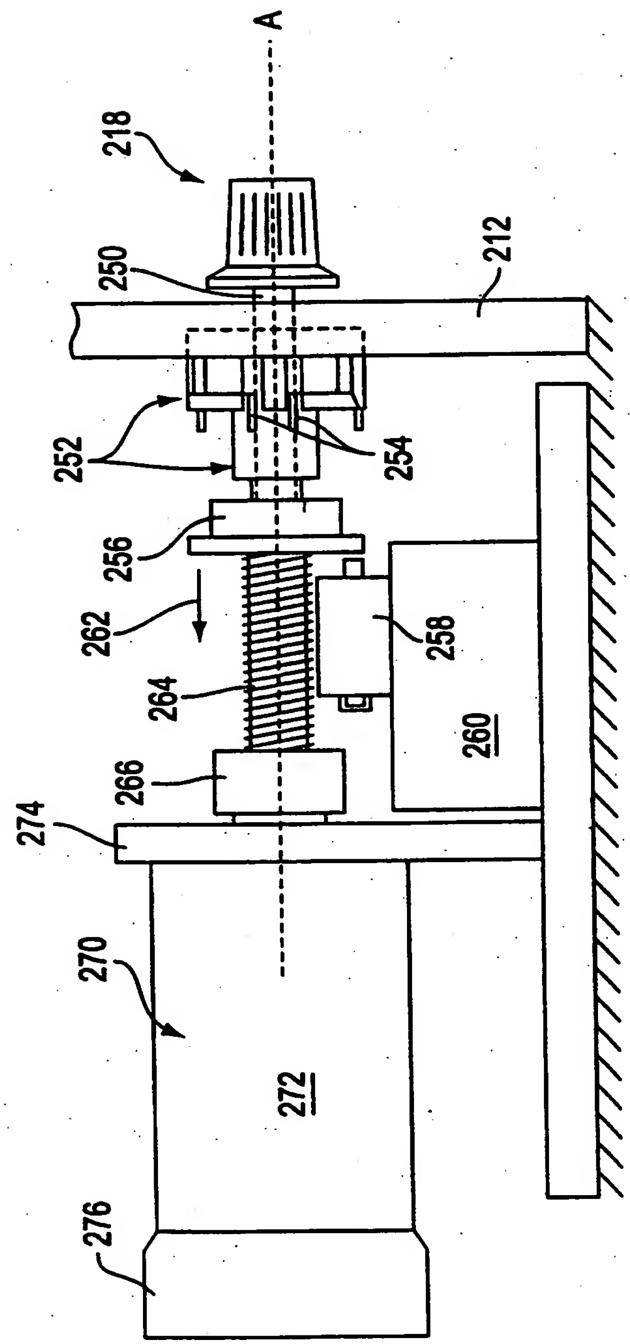

FIG. 12b

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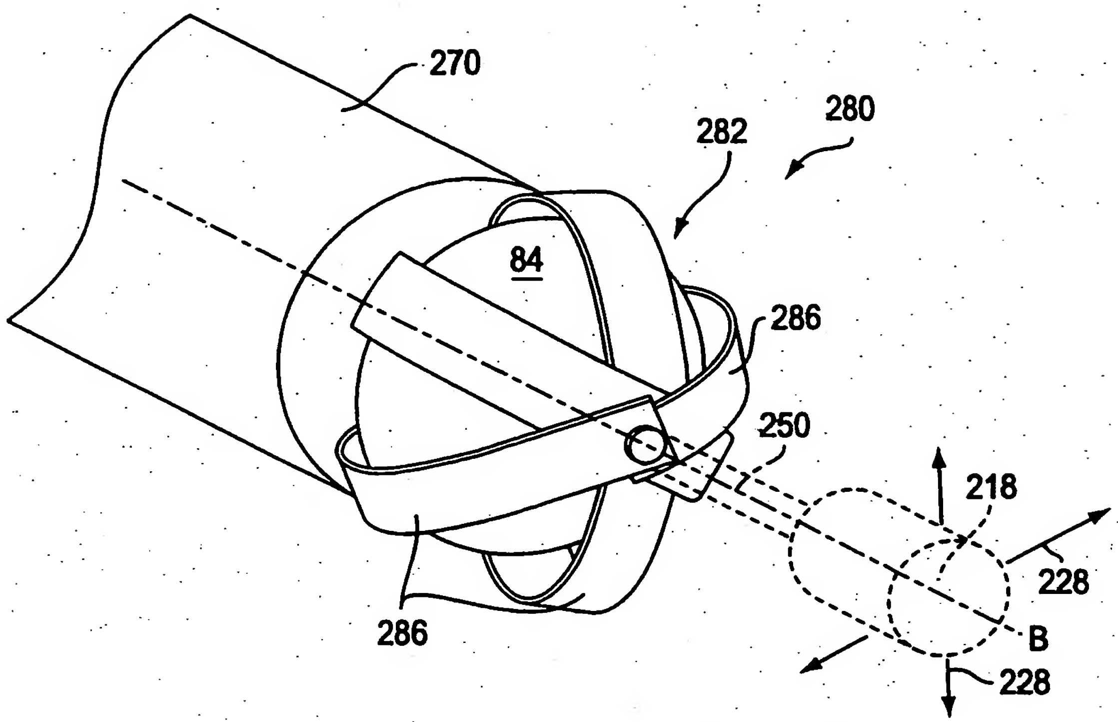

FIG. 13A

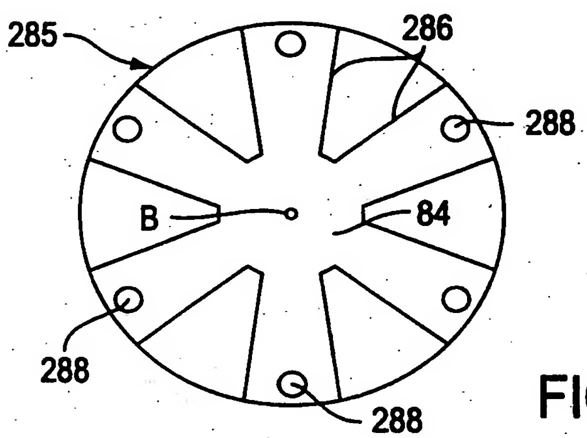

FIG. 13B

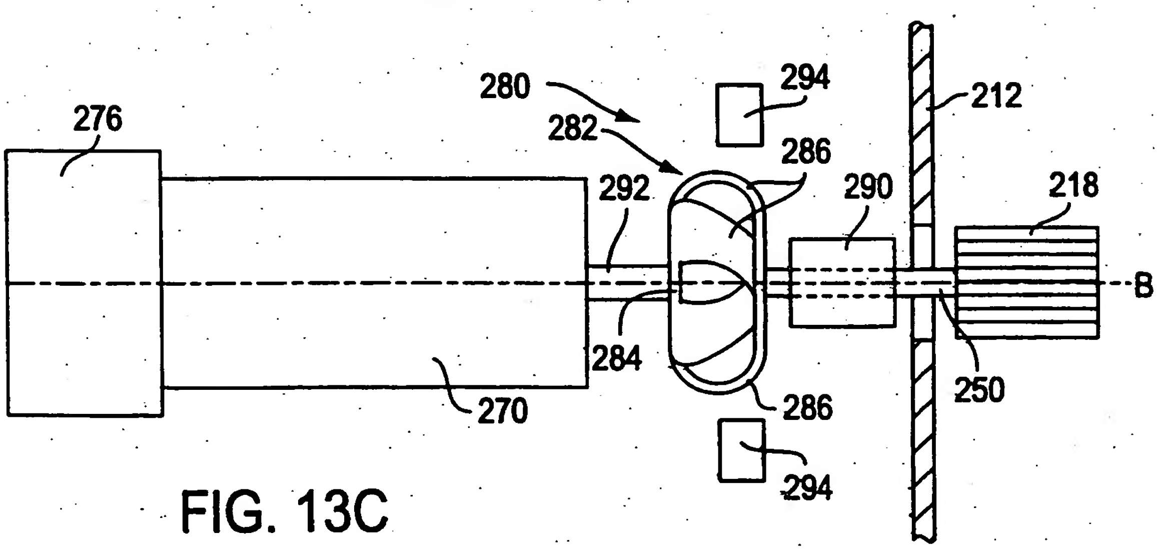

FIG. 13C

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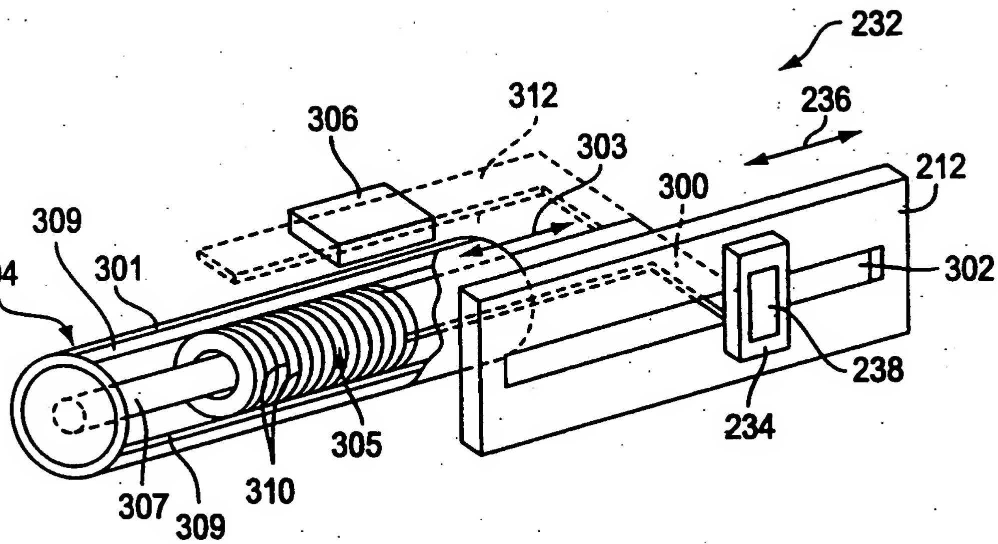

FIG. 14

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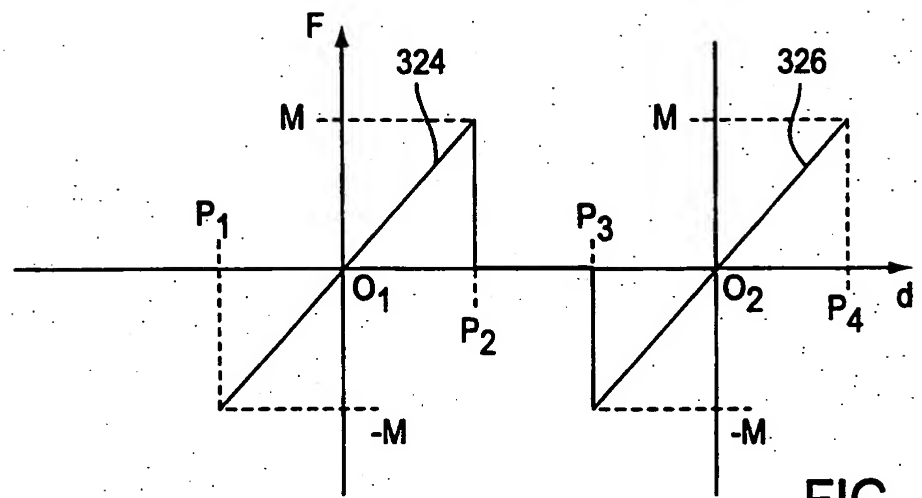

FIG. 15A

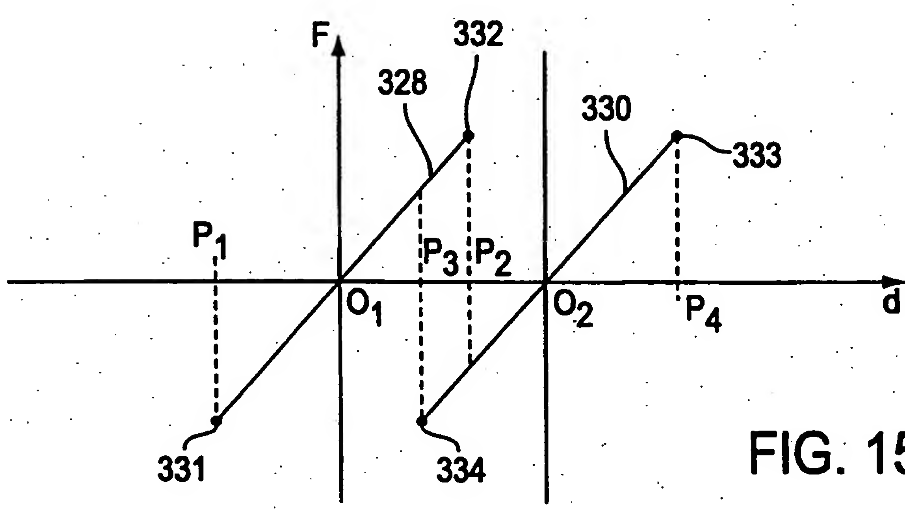

FIG. 15B

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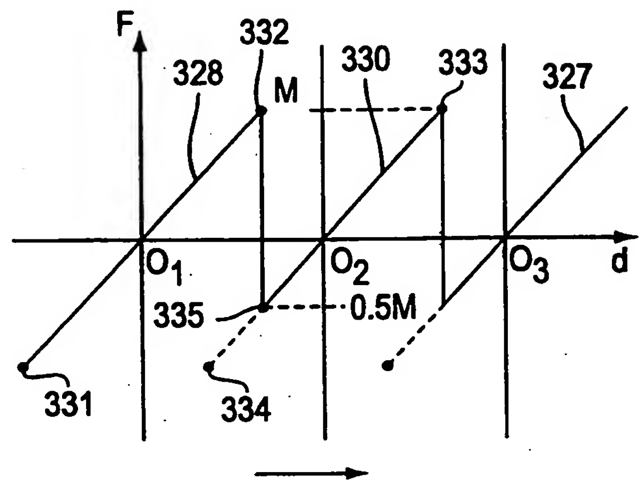

FIG. 15C

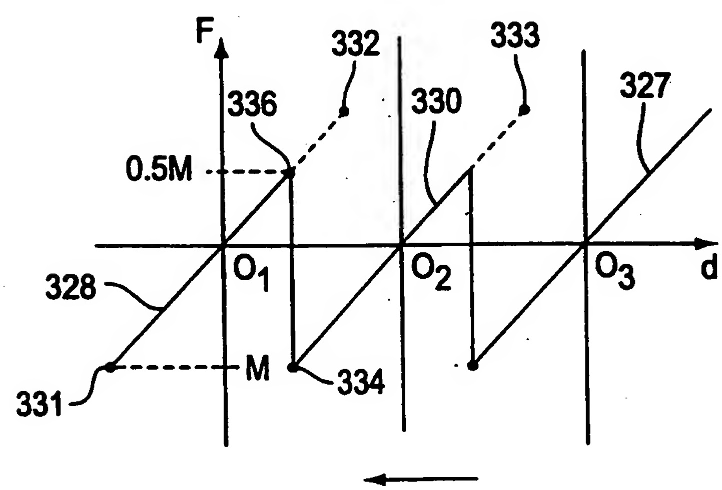

FIG. 15D

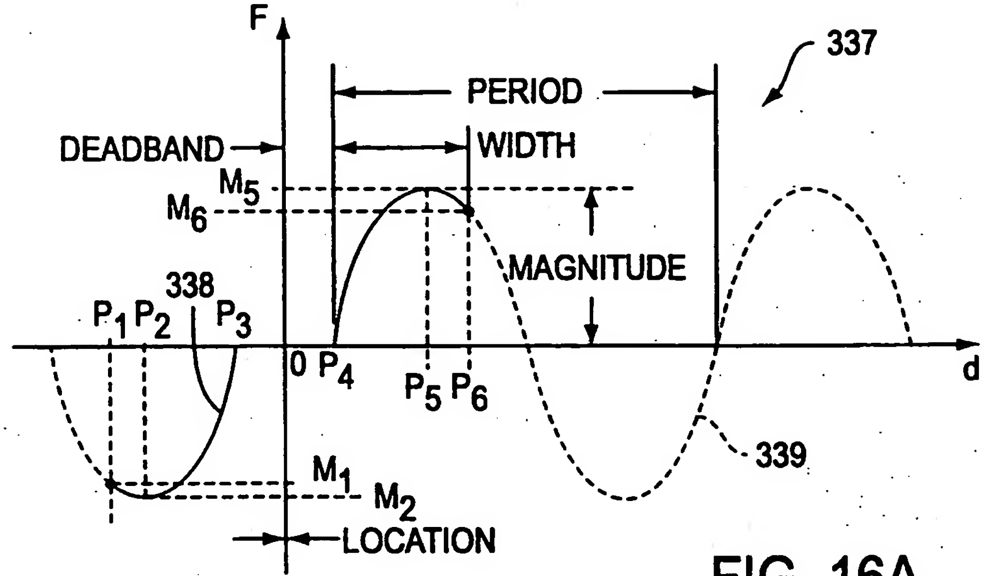

FIG. 16A

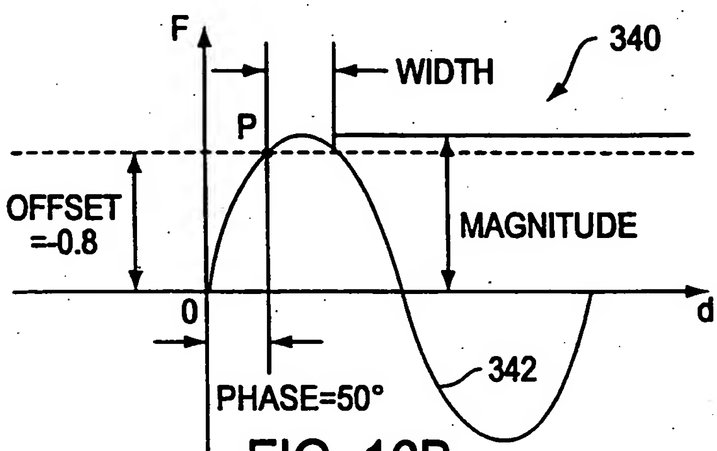

FIG. 16B

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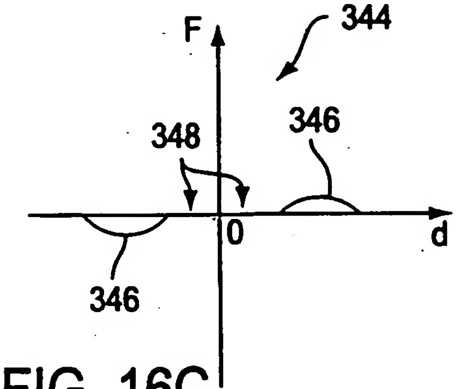

FIG. 16C

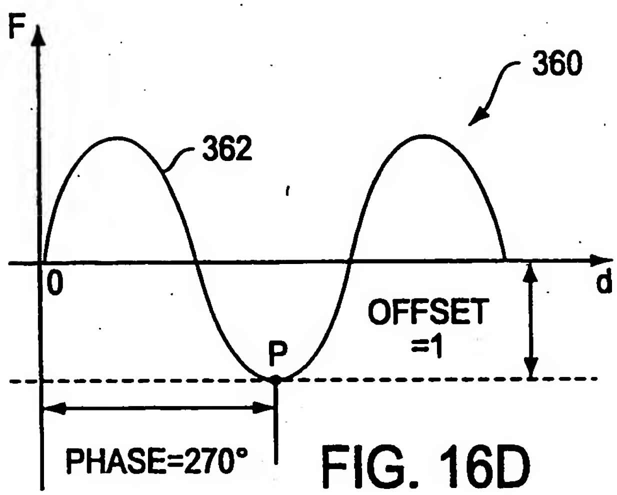

FIG. 16D

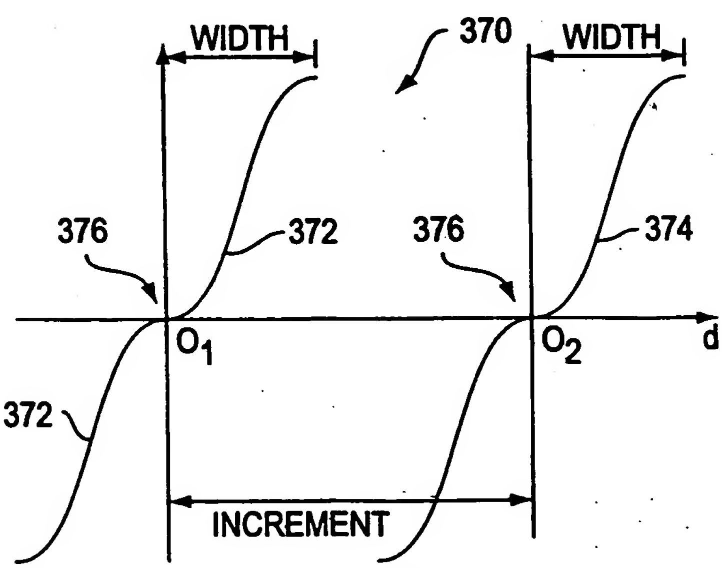

FIG. 16E

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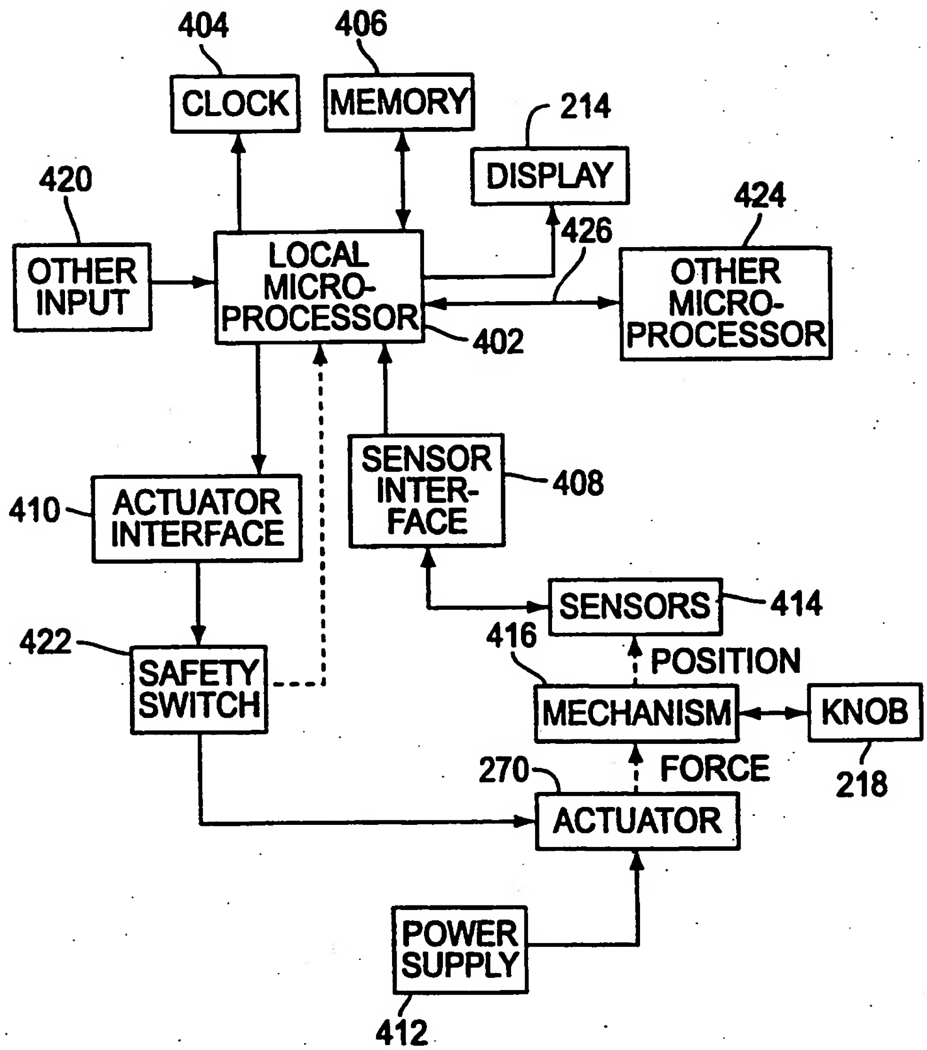
404
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CLOCK
MEMORY
214
DISPLAY
420
424
426
OTHER INPUT
LOCAL MICRO-PROCESSOR
OTHER MICRO-PROCESSOR
402
SENSOR INTER-FACE
408
410
ACTUATOR INTERFACE
SENSORS
414
422
416
POSITION
SAFETY SWITCH
MECHANISM
KNOB
270
FORCE
218
ACTUATOR
POWER SUPPLY
412

FIG. 17